Energy Research and Development Division
FINAL PROJECT REPORT

ENERGY REDUCTION IN MEMBRANE FILTRATION PROCESS THROUGH OPTIMIZATION OF NANOSUSPENDED PARTICLE REMOVAL

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PREFACE

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Energy Reduction in Membrane Filtration Process through Optimization of Nanosuspended Particle Removal is the final report for the Energy Reduction in Membrane Filtration Process project (contract number MRA-02-082) conducted by University of California, Irvine and Kennedy/Jenks Consultants. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

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ABSTRACT

Membrane processes are widely used in water reclamation and reuse. The process of membrane filtration is gaining ground and its energy intensity is being investigated as more tertiary processes are implemented for water reclamation. A better understanding of membrane fouling is key to reducing energy requirements, which in turn lowers operating costs. Nanomaterials have the potential to cause pore plugging of the membranes, which is very difficult to mitigate due to their small size. The goals of this study were to: (1) establish the fate of nanomaterial in wastewater streams; (2) evaluate the impact of select particle sizes on flux through microfiltration and ultrafiltration hollow fiber membranes; (3) determine potential flux improvements with pre-treatment (coagulation/sedimentation); and (4) estimate the energy reduction due to removal of nanomaterial. Particle size distribution and soluble chemical oxidation demand analysis was conducted on several samples throughout this study. Results showed that the count rate in the filtrate samples was reduced as wastewater samples were filtered with increasingly smaller pore sized filters. This result demonstrated that not only were the larger particles removed, but the overall number of particles was decreased by the filtration process. Flux analysis of microfiltration membranes (200 nanometer pore size) showed that particles between 100 and 2.5 nanometers contributed the most to membrane fouling. This also indicated that a significant portion of the fouling was due to nanoparticles clogging the pores within the membrane rather than fouling due to cake formation. Pretreating the wastewater with coagulants could remove up to 60 to 80 percent of nanomaterial and significantly reduce energy consumption from membrane filtration.

Keywords: Nanoparticles, hollow fiber membranes, flux, particle size distribution, coagulation, energy, wastewater

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Wastewater contains both dissolved and suspended constituents and the size distribution of suspended particles spans from macroscopic to nanoparticles. Nanoparticles are particles with sizes between 1 and 100 nanometers (nm). The behavior and removal of these suspended particles in wastewater treatment and water reclamation processes is heavily affected by the particle size. Particle size distribution is a key factor affecting process/energy efficiency in wastewater treatment processes.

Pretreatment techniques including coagulation/precipitation can potentially remove nanoscale particles prior to membrane filtration. In Southern California the total water reclaimed using membrane processes is estimated to exceed 300 million gallons per day (MGD). Membrane processes are widely used in water reclamation and reuse. Membranes are typically configured in incremental steps; membranes with larger pores are configured first using microfiltration (MF) or ultrafiltration (UF), followed ultimately by configuration of the smaller pores using reverse osmosis (RO). Membrane processes for water and wastewater treatment are highly energy intensive so it is crucial to understand the fouling mechanisms that affect energy variations during their operations to minimize overall energy usage.

Project Purpose

The first goal of this project was to investigate the role of biogenic nanoparticles present in secondary wastewater effluent on the fouling of membranes used for tertiary treatment for water reclamation. The second goal was to develop a relationship between type of membranes, water quality characteristics and the critical size of nanoparticles responsible for flux reduction.

The objectives to meet these goals involved performing field and bench-scale studies to evaluate the potential role of biogenic nanoscale materials on MF and UF membrane filtration efficiency and identifying ways to improve energy efficiency through removal/mitigation of nanoscale particles by completing the following tasks:

- Establishing nanoscale materials fate and removal in existing treatment processes.
- Evaluating the impact of sub-micron particles on flux reduction in MF and UF membranes.
- Pretreatment to remove nanoscale suspended particles.
- Estimating energy reduction due to removal of nanoscale suspended particles.

Project Results

Samples were taken at the primary influent, primary effluent, and secondary effluent points at three different wastewater treatment plants: Irvine Ranch Water District (IRWD), Orange County Sanitation District (OCSD), and Santa Margarita Water District (SMWD). These samples were incrementally filtered in series by select pore sizes to analyze varying size fractions of nanomaterial in wastewater. The samples were then analyzed for particle size distribution and soluble chemical oxidation demand (sCOD).

Secondary effluent samples from each treatment facility were collected and incrementally pre-filtered in series. Each size fraction sample was pulled through individual membrane fibers and the change in flow was measured to determine the fouling potential. Analyses of particle size distributions were conducted on the feed and permeate samples.

Removal of suspended nanoscale material was completed by adding select concentrations of a coagulant to SMWD secondary effluent. Particle size distribution and sCOD analysis were conducted to determine the removal of nanomaterial. In addition, flux experiments were run on the pre-treated samples using MF membranes to determine if flux improved with the reduction of nanomaterial.

Energy reduction was then estimated based on the flux results gathered from previous experiments conducted during this project.

The project established the fate of nanomaterial in several processes. Results showed that the count rate in the samples was reduced as the pore size became smaller. This result demonstrated that not only were the larger particles removed, but the overall number of particles in various size ranges was decreased by the filtration process. During the same incremental filtration series sCOD did not vary, showing that the largest contribution to sCOD was the small particles or the dissolved constituents that bypass all the filtration events. An activated sludge process at IRWD with a high mean cell residence time (MCRT) removed particles at each size range more effectively. Trickling filtration at SMWD was shown to be the least effective process for removing nanoscale material but this may have been due to the higher number of particles received by the plant.

Researchers made the following observations from the results of the flux analysis:

- The membrane fiber fouled more rapidly as the particle sizes increased.
- There were no significant differences in fouling between 450 nm and 100 nm particles.
- Samples pre-filtered with a 3.5 nm membrane contributed as much as 50 percent of the subsequent membrane fouling.
- Samples pre-filtered to 2.5 nm had similar de-ionized (DI) water flux results.
- Pore plugging seen in MF fibers was due to larger pore size while UF fibers had a much small pore size and fouling due to pore plugging was not observed.

Coagulation experiments showed that as the coagulant concentration increased the amount of sCOD removed also increased. However, no single coagulant tested at equivalent concentrations appeared to improve water quality. Particle sizes initially increased with coagulant concentration but at a point particles began to settle out of solution and particle size decreased. Flux analysis also showed that as the concentration increased the fouling of the membranes was reduced.

Energy analysis of previous experiments in this study showed that the fouling of a membrane is directly related to the energy consumption. As the flux through the membrane decreased due to

fouling by nanomaterial there was an equivalent increase in energy used. Unfiltered samples required the most energy while samples pre-filtered to 2.5 or 3.5 nm did not significantly alter the energy required for filtration. While there were no significant differences between the energy consumption of each coagulant used in this experiment, results showed that a concentration of only 10 milligrams per liter (mg/L) could reduce power consumption about by 20 to 30 percent. A relatively small amount of coagulant could significantly reduce membrane fouling, resulting in energy conservation.

Nanoscale particles appeared to foul microfiltration membranes employed in tertiary filtration in any of the experiments performed. This was indicated as a membrane flux reduction, with associated reduction in membrane throughput or increase in trans-membrane pressure. As a consequence the energy used for filtration increased rapidly and caused significant energy wastage. The relative increase in energy usage for microfiltration may be several times the initial energy. Selective pre-treatment performed as progressive filtration of nanoparticles indicated that nanoscale particles with sizes larger than 3.5 nm had the strongest effect on flux reduction and therefore on energy wastage.

Project Benefits

A survey of RO facilities in the Southern California service area indicated that there are 16 reclamation facilities, eight desalination facilities, 26 brackish water facilities, five municipal water treatment facilities serving more than 500 people, and 18 small municipal water treatment facilities serving less than 500 people. The design flow rates for 54 out of the 73 facilities were obtained. The total flow rate for the facilities with known flow rates was about 315 MGD. The overall treatment capacity of these facilities varied from 0.1 to 90 MGD. For the remaining facilities, assuming an average flow rate of two MGD for the larger systems and 0.25 MGD for the smaller systems, the total water treated by membrane processes in the project area was about 330 MGD.

Furthermore, a survey by the American Membrane Technologies Association indicated that there are at least 345 microfiltration treatment plants (88 MGD capacity), two nanofiltration facilities (nine MGD capacity), 31 RO facilities (93 MGD capacity) and six UF facilities (42 MGD capacity) in California. This is not a complete list as it does not include some major filtration facilities including the 70 MGD Orange County Water District (OCWD) MF facility. Industrial membrane treatment facilities were also not included in this compilation.

There is potential to improve the energy efficiency of these membrane treatment facilities in California, as well as other industrial/municipal membrane treatment facilities outside of California.

CHAPTER 1:
Introduction

1.1 Background

In wastewater treatment process, particle size distribution is long considered a key factor that impacts process/energy efficiency. Most of the historic studies on particle size distribution focused on micron (or larger) size fraction. Micron (or larger) size particles can impact coagulation/precipitation, membrane filtration, activated sludge, disinfection and solids dewatering during water / wastewater treatment. Several studies have been performed to improve treatment process efficiency, which in many cases resulted in energy conservation.

Although several studies have been performed to improve water and wastewater treatment efficiency through removal of larger size particles, very little studies have been performed to date to understand the role of sub-micron/nanoscale suspended particles. Limited data available in literature indicate that sub-micron/nanoscale fraction of suspended solids in water/wastewater may play a more significant role than micron (or larger) size particles with respect to process/energy efficiency. For example, 2 to 500 nm size fractions of suspended particles appear to foul membrane elements (MF, UF, reverse osmosis [RO]) more permanently, resulting in larger energy demand during water treatment (1,2). Also, polymer dosing at current sludge dewatering processes do not capture nanoscale suspended particles effectively. Evidence in literature indicates that capture of these particles can significantly conserve energy during sludge dewatering (3).

Although sporadic data are present, to date no systematic studies have been done to evaluate i) the role nanoscale particles in the energy demand during wastewater treatment, and ii) methods to optimize their removal to improve energy efficiency. With the emergence of nanotechnology new tools are now available to detect/monitor nanoscale materials in wastewaters.

To date very little systematic studies have been done to evaluate the impact of nanoscale constituents on wastewater treatment processes. Available information on the removal of nanoparticles by membrane filtration processes and coagulation (as pretreatment to membrane) is briefly summarized below.

1.2 Nanoscale Particles and Membrane Filtration

Membrane processes for water and wastewater treatment are highly energy intensive. Depending on the water quality characteristics, energy requirements for treating about 1 million gallons of water may range from 600 to 800 kW for MF membranes to 1600 to 2000 kW for RO membrane. A limited number of modeling and laboratory scale studies have evaluated the impact of colloidal particle size on the fouling of pressurized membranes (4, 5). A theoretical model developed by Wiesner and Chellam (4) suggested that individual or agglomerated nanoparticles of about 100 nm have the highest potential to foul the membranes. Particles larger and smaller than 100 nm had a lower impact on membrane fouling. However, deviations to

these predictions were observed in studies using different membrane systems, as well as the type of nanoparticles, as discussed below:

OCWD, our partners for this study, have performed detailed studies to evaluate fouling of MF membranes by submicron suspended particles in their secondary treated wastewater (2, 6). In their study, they compared the fouling characteristics of the unfiltered wastewater with that of wastewater samples pre-filtered using 200, 3.5 and 2.5 nm pore size cartridges. Their studies indicated that, biogenic nanoparticles of sizes smaller than 200, 3.5 and 2.5 nm were cumulatively responsible for about 88, 45 and 5 percent, respectively, of total flux reduction caused by untreated secondary effluent (Figure 1).

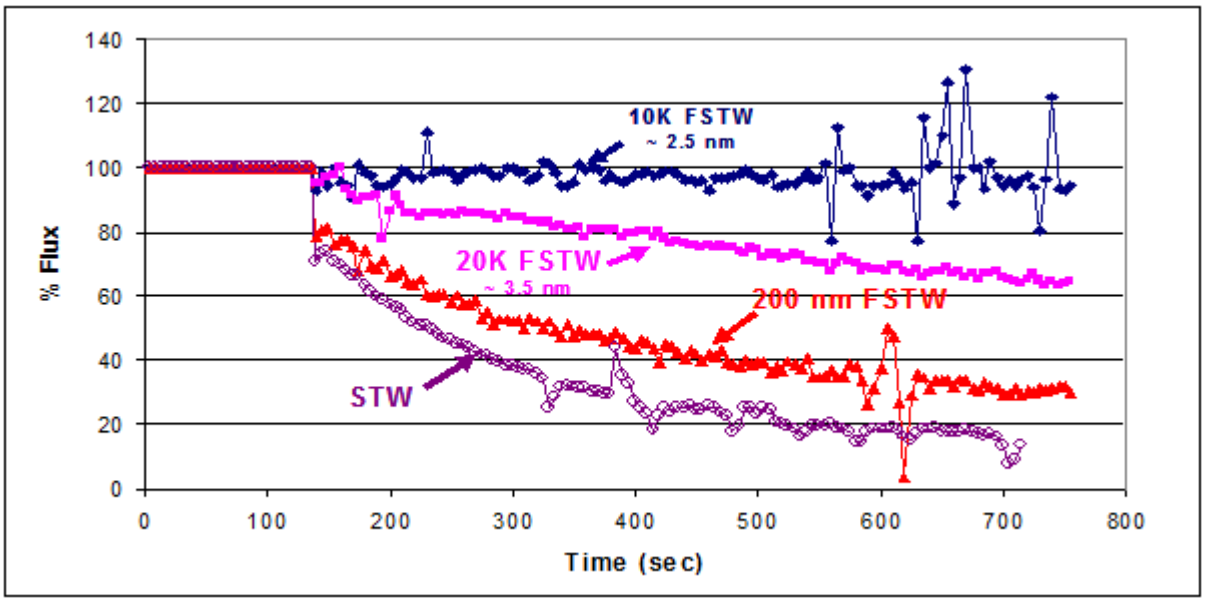

Figure 1: Flux Reduction in MF Membranes by Nanoscale Suspended Particles Using OCSD Secondary Treated Effluent (Studies performed by OCWD, (2))

In a European study, biogenic nanoscale particles of 100 to 200 nm size fraction in the wastewater was largely (40 – 57 percent) responsible for fouling of UF membranes (7). Particles larger than 200 nm were responsible for 30 to 36 percent of the membrane fouling, and those smaller than 100 nm caused 12 to 29 percent of membrane fouling.

Microfiltration of nanosilica (80 to 200 nm, 800 mg/l) from semiconductor chemical/mechanical polishing (CMP) wastewater removed approximately 50 percent and 90 percent of the nanosilica without and with pre-coagulation, respectively (8). In a laboratory study using nanoscale latex beads, particles at 500 nm size were largely responsible for fouling of cellulose acetate membranes (9). In a different laboratory study, cross-flow MF/UF tests using nanosilica materials indicated that cake porosity on MF membrane was larger than that of UF membrane (10). However, the rate of flux decline in MF membrane was more than that of UF since the

ratio of the cake resistance to membrane resistance is disproportionately larger in MF membrane.

In summary, nanoscale materials appear to have significant impact on membrane fouling and hence, flux reduction and energy use. However, the extent of impact and the (nano) size fraction that affects the membrane appear to vary with membrane type, membrane material and water quality characteristics.

1.3 Coagulation of Nanoscale Materials

Pretreatment techniques, including coagulation/precipitation can potentially remove nanoscale particles prior to membrane filtration. However, to date only limited number of studies has been performed to specifically remove nanoscale suspended particles by coagulation/precipitation techniques. In a study performed by this project team member (Kennedy/Jenks Consultants), conventional polymer treatment removed only about 65 percent of nanosuspended particles from municipal wastewater sludge (Figure 2). (Subsequently, a specially designed polymer additive, by the project team member, Kennedy/Jenks Consultants, removed more than 90 percent of the nanoscale particles that were NOT removed by the conventional polymer treatment).

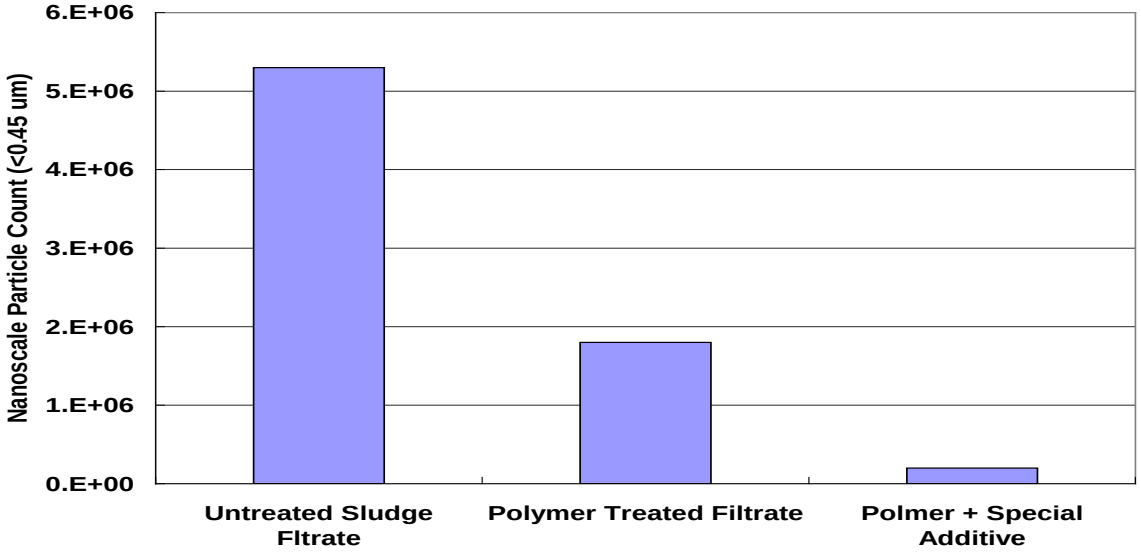

Figure 2: Nanoscale (< 450 nm) Particle Count in Untreated and Polymer Treated Sludge Filtrate. Polymer Treatment Removed Only About 65% of the Submicron Particles.

In yet another study coagulation using aluminum polysulfate removed about 90 percent of the submicron (< 500 nm) suspended particles from a slaughterhouse wastewater (11). However, the optimum reaction time (5 minutes coagulation, 60 minutes flocculation, and 60 minutes settling) was significantly longer than typical reaction times used in treatment plants. Furthermore, this study did not systematically evaluate the particle size range below 500 nm. In another study using manufactured nanoparticles, only about 40 to 60 percent of metal oxide

nanoparticles were removed by alum and ferric coagulation (12). Nearly 10 to 30 percent of initial concentration remained in suspension after coagulation followed by filtration (0.45 μm).

No systematic study has been performed using other pretreatment processes (e.g. adsorption, ion exchange) to specifically remove nanoscale suspended particles from wastewater.

In summary, current knowledge on the pretreatment of nanoscale suspended particles appear to be very limited. Available data appear to indicate that current techniques are not very effective in removing nanoscale particles, and modifications are required to optimize pretreatment processes for targeted removal of nanoscale particles.

1.4 Energy Implications

A survey of RO facilities in Southern California service area indicated that there are 16 reclamation facilities, 8 desalination facilities, 26 brackish water facilities, 5 municipal water treatment facilities serving more than 500 people, and 18 small municipal water treatment facilities serving less than 500 people (13). The design flow rates for 54 out of the 73 facilities were obtained. The total flow rate for the facilities with known flow rates is about 315 MGD. The overall treatment capacity of these facilities varied from 0.1 to 90 MGD. For the remaining facilities, assuming an average flow rate of 2 MGD for the larger systems and 0.25 MGD for the smaller systems, the total water treated by membrane processes in the project area is about 330 MGD.

Furthermore, a survey by American Membrane Technologies Association indicates that there are at least 345 microfiltration treatment plants (88 MGD capacity), 2 nanofiltration facilities (9 MGD), 31RO facilities (93 MGD) and six UF facilities (42 MGD) in California (14). This list is not a complete list as it does not include some major filtration facilities including the 70 MGD OCWD MF facility. Industrial membrane treatment facilities are also not included in this compilation.

There is potential to improve the energy efficiency of these membrane treatment facilities in California, as well as other industrial/municipal membrane treatment facilities outside California.

1.5 Project Goals

The goal of this project is to investigate the role of biogenic nanoparticles present in secondary wastewater effluent on the fouling of tertiary membranes for water reclamation. In order to do so, we performed bench-scale studies to evaluate potential role of biogenic nanoscale materials on membrane (UF and MF) filtration efficiency, and identify ways to improve energy efficiency through removal/mitigation of nanoscale particles. A secondary goal of this project is to initiate development of relationship between the type of membranes, water quality characteristics and the critical size of nanoparticles responsible for flux reduction (and energy use).

CHAPTER 2:
Project Approach

In this study there are four distinct tasks that were proposed to be completed;

Task 1. Establish nanoscale materials fate and removal in existing treatment process

Task 2. Evaluate impact of sub-micron particles on flux reduction in MF and UF membranes

Task 3. Pretreatment to remove nanoscale suspended particles

Task 4. Estimation of energy reduction due to removal of nanoscale suspended particles

A description and summary of these tasks are presented below:

2.1 Fate and Removal of Nanoscale particles In Existing Treatment Plants

Under this task, a detailed evaluation of fate and removal of nanoscale materials in three major wastewater treatment processes was performed. The treatment plants include i) the water reclamation facility at IRWD, ii) the trickling filter plant at Santa Margarita Water District, and iii) the activated sludge treatment plant at OCWD. The treatment process at Michelson treatment plant at IRWD includes screening, primary settling, activated sludge process, secondary clarification, dual media filtration and disinfection. The existing treatment processes in Santa Margarita Water District, Chiquita reclamation plant (6 MGD) include influent pumping, grit removal, primary clarifiers, trickling filters/solids contact, anaerobic digestion and belt filter presses for dewatering. During water reclamation, OCWD receives secondary treated wastewater from OCSD that undergoes screening, advanced primary clarification, activated sludge process, disinfection (and anaerobic digestion). For the proposed study, effluent samples (duplicate) from various unit processes (e.g. primary influent, settling tank, secondary effluent, media filters) were analyzed for distribution of biogenic nanoscale materials. Analyses included i) nanoscale particle size distribution using a nanoparticle counter (Malvern Zetasizer) at UCI, and , ii) sCOD analyses to relate the nanoscale particle size distribution to equivalent sCOD in the wastewater samples.

2.2 Evaluate Impact of Sub-micron Particle Size on Flux Reduction in MF and UF Membranes

This task evaluated the relationship between nanoparticle size range and membrane type / membrane materials. The secondary treated water from the three wastewater treatment plants identified in Task 1 was used in this task. Membrane type evaluated includes ultrafiltration (UF) and microfiltration (MF). Initially, RO membranes were potentially thought as part of the domain of this study. However, the significant reduction in flux recorded in the upstream MF and UF membrane stages (and consequent low amount of nanoparticles in the RO membrane influent) directed our research efforts to the MF and UF membranes, which would best serve the ultimate goal of energy reduction in membrane filtration.

Figure 3 shows the schematic of the experimental setup. The flask containing 250 ml secondary treated wastewater is constantly stirred in a stirring table. The sample is drawn to the 50 ml vial containing 20 cm long dead-end filtration fiber (e.g. US Filter, M10CPP, 0.2 μm pore MF fiber) at -5 psi vacuum pressure. The filtered water is collected in a collection vial placed on an electronic balance. The mass of filtered water in the collection vial is continuously measured, converted to flux rate and recorded in the computer using the Win Wedge program (Tal Tech, PA). The experiment was stopped after a 95 percent flux drop. The feed and permeate waters were analyzed for sCOD concentration, particle size distribution and turbidity.

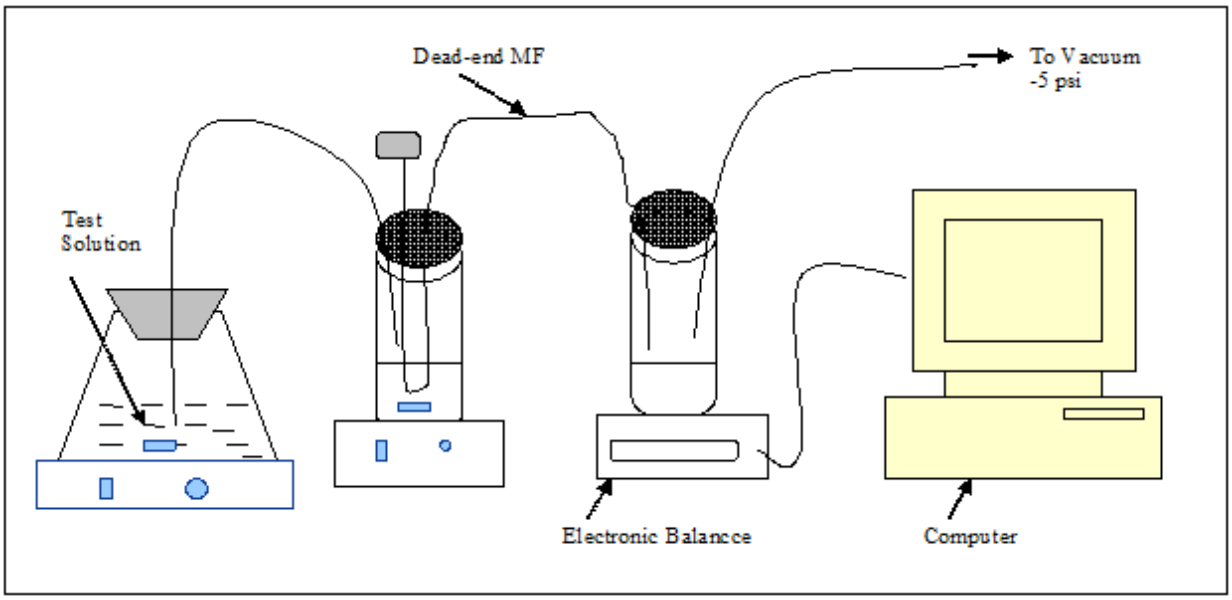

Figure 3: Experimental Arrangement to be Used for Membrane Filtration Studies.

Furthermore, in order to understand the impact of specific size range of nanoscale particles, the secondary effluents were pre-filtered using membranes of different pore size. Bench scale AMI membranes of 2.5 nm, 3.5 nm, 100 nm, 200 nm and 450 nm (e.g. MU1812PAN40050 (20,000 MW cutoff); M-U182PES50 (10,000 MW cutoff)) were used to pre-filter the samples and used for the filtration studies shown in Figure 1. A relationship between particle size and flux drop were developed and the critical particle size range responsible for major membrane fouling for different wastewaters and membrane types were identified. Table 1 summarizes various factors that were evaluated during the bench scale membrane studies.

Table 1: Summary of Factors Evaluated for Nanoscale Particles Impact During Membrane Filtration

Wastewater	Pre-Filtration	Membrane Type
1. IRWD Activated Sludge Treatment Effluent 2. SMWD Trickling Filter Effluent 3. OCWD Activated Sludge Secondary Effluent	1. Unfiltered 2. 450 nm 3. 200 nm 4 .100nm 5. 3.5 nm 6. 2.5 nm	1. Microfiltration – 200 nm nominal pore size Polypropylene material 2. Ultrafiltration – 45 nm nominal pore size PVDF material (designated as PVDF1) 3. Ultrafiltration – 45 nm nominal pore size PVDF material made by an alternate manufacturer (designated as PVDF2)

2.3 Pretreatment to Remove Nanoscale Suspended Particles

Pre-treatment techniques (coagulation/precipitation) were performed to evaluate removal of nanoscale suspended particles from the secondary effluent from the three wastewater treatment facilities.

Coagulation/precipitation studies were performed using a Phipps & Bird jar tester containing six paddles. Three coagulants (alum, ferric chloride and Sumaclear 1000, an aluminum polychloride based polymer, Summit Research Lab, NJ) were used. Three concentrations of each coagulant (alum 20, 40 and 50 mg/l; ferric chloride 25, 50, 75 mg/l; polymer 10, 15, 20 mg/l) were used. The alum and ferric chloride concentrations were selected based on Kennedy/Jenks Consultants previous studies for a California Central Coast wastewater treatment plant (WWTP) effluent (15). The polymer dose is selected based on earlier OCWD studies (2, 6). Six 1L jars containing 700 mls of samples will be used in each jar test. Upon coagulant addition, the samples were rapidly mixed at 120 rpm for 1 minute and slowly mixed at 30 rpm for 10 minutes, and then allowed to settle for 10 minutes. Supernatants were collected and analyzed for nanoscale particle size distribution, sCOD levels, zeta potential, turbidity and pH to determine the role of various parameters on coagulation of nanoscale materials in wastewaters.

2.4 Estimation of Energy Reduction Due to Removal of Nanoscale Suspended Particles

This task evaluated i) the demand exerted by various size fractions of biogenic nanoparticles, and ii) net energy savings resulting from the removal of nanoscale particles using various pre-treatment techniques, during membrane treatment of the wastewaters used in this study. The underlying hypothesis of this evaluation is that, the pretreatment for removal of nanoscale foulants will lower the flux drop across the membrane, resulting in lower energy use during treatment. The relationship between the flux rate and energy demand can be expressed using the following equation:

Energy for Filtration (kWh) = $F \times (P_A/A) \times (2.31 \times 0.746/3960)$ (1)

Where, F = filtrate flow rate in liters/minute; Pa/A = Vacuum pressure per unit filter area (Psi).

The energy conserved due to removal of nanoscale particles through pretreatment were estimated using the following equation:

E_{cons} (kWh) = $(F_T - F_U) \times (P_A/A) \times (2.31 \times 0.746/3960)$ (2)

Where, E_{cons} is the energy conserved due to pretreatment for removal of nanoscale particles, F_T is the flow rate of the pretreated secondary effluent, and F_U is the flow rate for the untreated secondary effluent.

The flow rate for the two systems will be assessed after the time that is required for a drop of 95 percent in flux rate for the untreated effluent.

2.5 Analytical Methods

2.5.1 Nanoparticle Counter

Particle size distributions for nanomaterials in various samples were measured using a Malvern Zetasizer ZS sub-micron particle counter at UCI facility. This equipment has been successfully used for analyses of a variety of nanomaterials (e.g. nanosilica, nano zero-valent iron) from industrial and laboratory samples (16, 17). An output from the Zetasizer during analyses of secondary effluent from OCWD at University of California, Irvine (UCI) is shown in Figure 4. Nanoparticles distribution at 85 nm size range was effectively captured by the instrument. Zetasizer uses a non-invasive back scatter (NIBS®) technology that facilitates particle sizing to sensitivity in the 0.6 nm to 6 micron range. This is achieved by a combination of laser Doppler velocimetry and phase analysis light scattering (PALS) technique. Required sample volume is less than 1 ml. It has been shown through statistical analysis that the count rate can be a useful technique to qualitatively measure relative nanoparticle removal in wastewater (18). The photon count rate measured was used to determine relative number of particles in various samples.

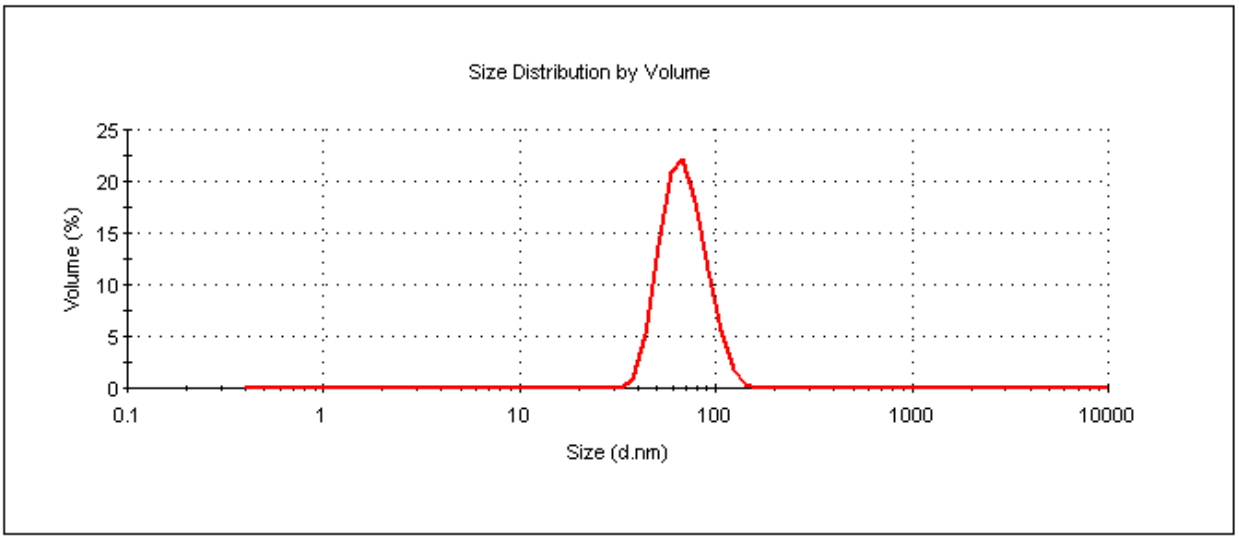

Figure 4: Biogenic Nanoparticle Size Distribution of the OCSD Secondary Effluent Measured Using Malvern Zetasizer ZS at UCI Laser Spectroscopy Facility.

2.5.2 Other Supernatant Analytical Methods

Samples were analyzed for sCOD using Hach colorimeter (Hach Method 8000). Turbidity and pH analyzes were performed at UCI laboratory using Standard Methods.

CHAPTER 3:
Project Outcomes

The fate of biogenic nanomaterial within existing wastewater treatment plants are presented in section 3.1. This experiment analyzed sCOD and particle size distribution for several points within three different treatment plants. The results show how differences in the treatment process affect the fate of biogenic nanomaterial. The next section (3.2) focuses on the impact of nanomaterial on microfiltration and ultrafiltration membranes. The results from this experiment show the fouling potential of several size ranges of nanomaterial found within secondary treated effluent. The following experiments in section 3.3 take the next step by pre-treatment the secondary effluent wastewater with coagulants in order to remove nanoparticles from suspension and reduce fouling within the membranes. The last sub-section in this report, 3.4, addresses the power consumption due to membrane fouling which is discussed in the previous sections.

3.1 Fate and Removal of Nanoscale Particles in Existing Treatment Processes

In order to determine the fate of nanoparticles in wastewater treatment primary influent, primary effluent and secondary effluent samples were collected from three treatment plants (OCSD, SMWD and IRWD). Samples were filtered in series from 450 nm to 10 nm and each filtrate was analyzed for particle size and sCOD. The results from each plant are discussed below:

3.1.1 Nanoparticles in OCSD Activated Sludge Treatment Process

Results are seen in figures 6, 7, and 8. All the results show a strong correlation between the count rate and filtration pore size (> 0.90) which means that as the pore size decreases the number of the particles within the sample decreases linearly. It appears nanoparticles are evenly distributed through from the 450 nm to 10 nm sizes; there is no size range where there is an abnormal amount of particles. When relating different processes within the treatment plant, the count rate noticeably decreases as the wastewater travels through each process. At the 450 nm filtration step in the primary influent sample the count rate is highest at 600 kcps then decreases to approximately 450 kcps in the primary effluent and then finally to 175 kcps in the secondary effluent sample. Subsequent filtration steps show proportional decreases in the number of particles. A decrease in the count rate in the primary treatment process is likely due to interception of nanomaterial by the settling of much larger particles. A decrease in the number of nanoparticles in the secondary treatment process is likely due to adsorption to microbial flocs or consumption by the microbes. Soluble COD is shown to have not been effected within any of the filtration steps seen in this experiment. A majority of the sCOD is contributed to particles or dissolved constituents smaller than 10 nm.

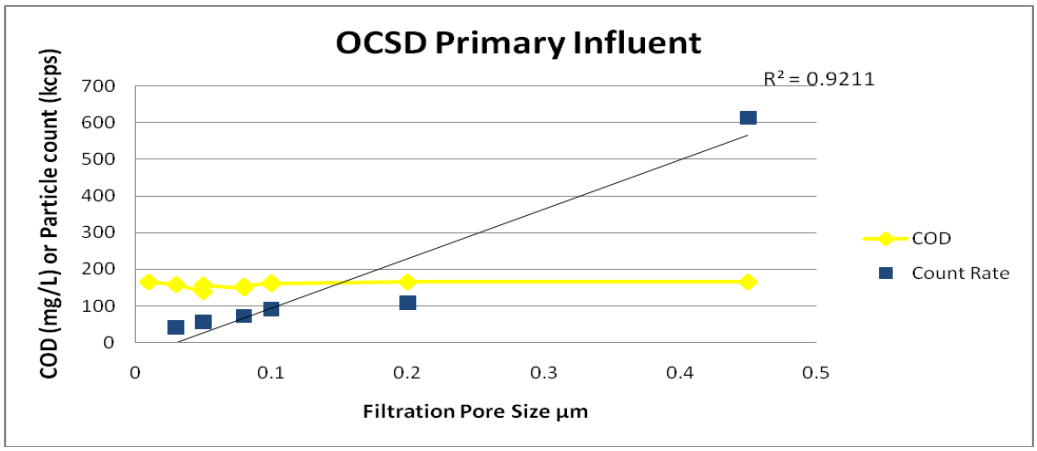

Figure 6: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of OCSD Primary Influent Wastewater

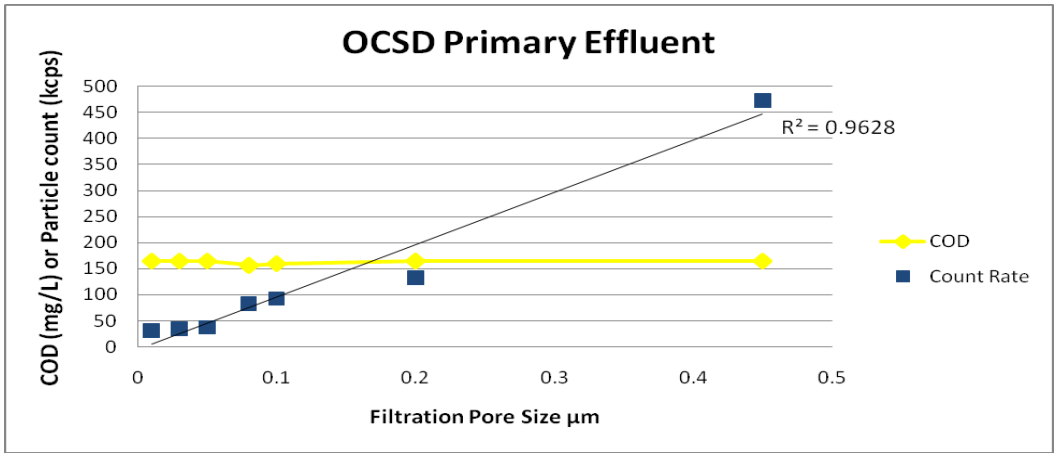

Figure 7: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of OCSD Primary Effluent Wastewater

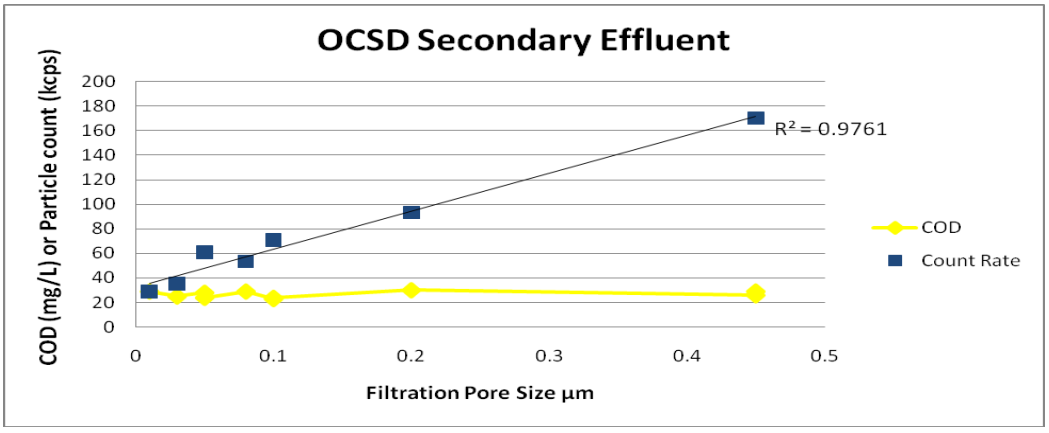

Figure 8: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of OCSD Secondary Effluent Wastewater

3.1.2 Nanoparticles in IRWD Activated Sludge Treatment Process

IRWD results are show in figures 9, 10 and 11. These results were expected to be similar due to similar treatment processes. However, primary influent has significantly less nanoscale particles than the primary effluent sample. It is possible that the removal of the larger particles through the primary treatment process exposes the smaller nanoscale particles in solution. There is a strong correlation in both primary influent and effluent figures between the count rate and pore size. However, the secondary effluent sample shows low correlation which may be due to a relatively low number of particles in the 450 nm filtration step. This shows that particles are removed very well at this specific size range due to a higher MCRT.

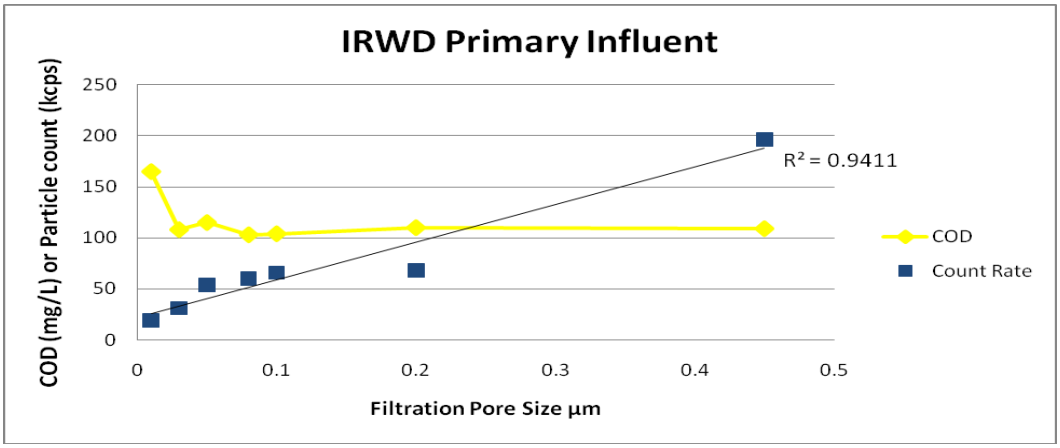

Figure 9: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of IRWD Primary Influent Wastewater.

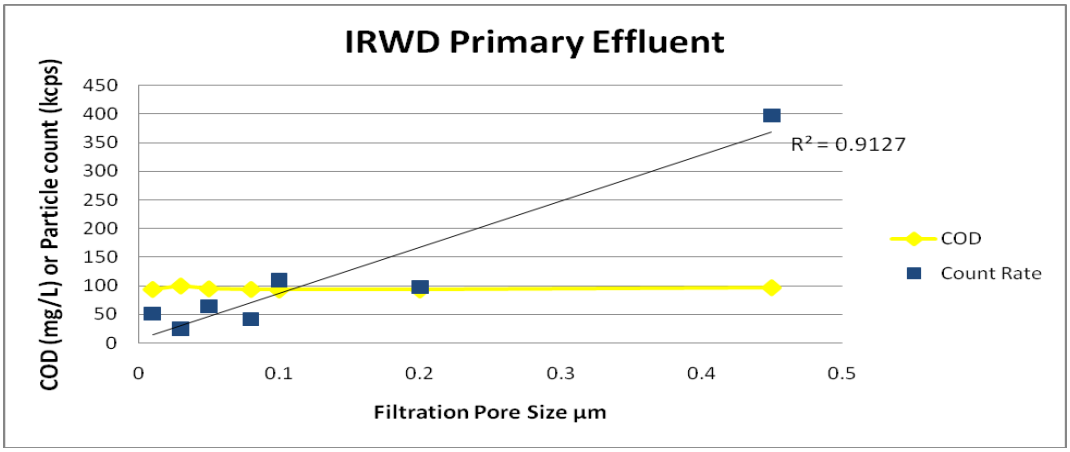

Figure 10: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of IRWD Primary Effluent Wastewater

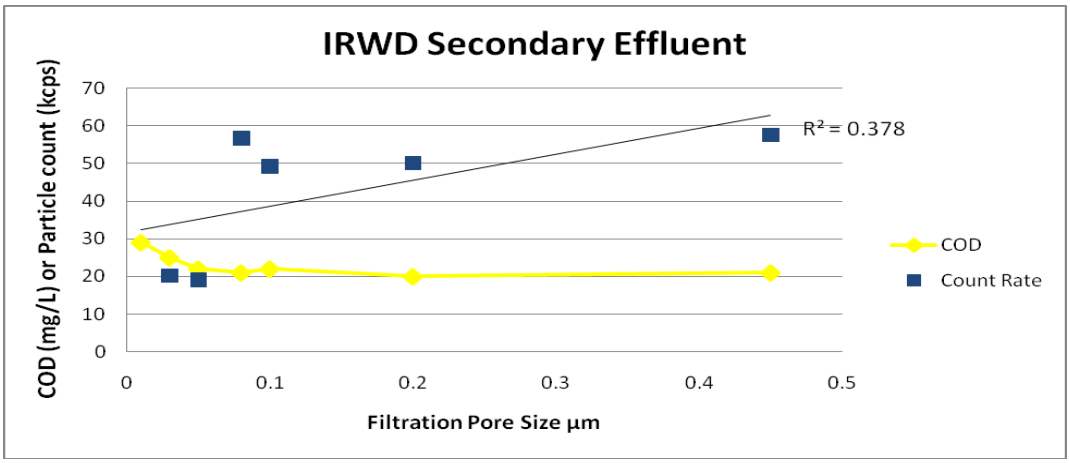

Figure 11: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of IRWD Secondary Effluent Wastewater

3.1.3 Nanoparticles in SMWD Trickling Filter Effluent

SMWD results are shown in figures 12, 13, and 14. We see similar trends as with previous treatment plants but the count rate is significantly higher in all the samples. This may be due to the characteristics of the wastewater that SMWD receives. In addition, the treatment process (trickling filtration) may not be as effective at removing smaller nanoscale particles.

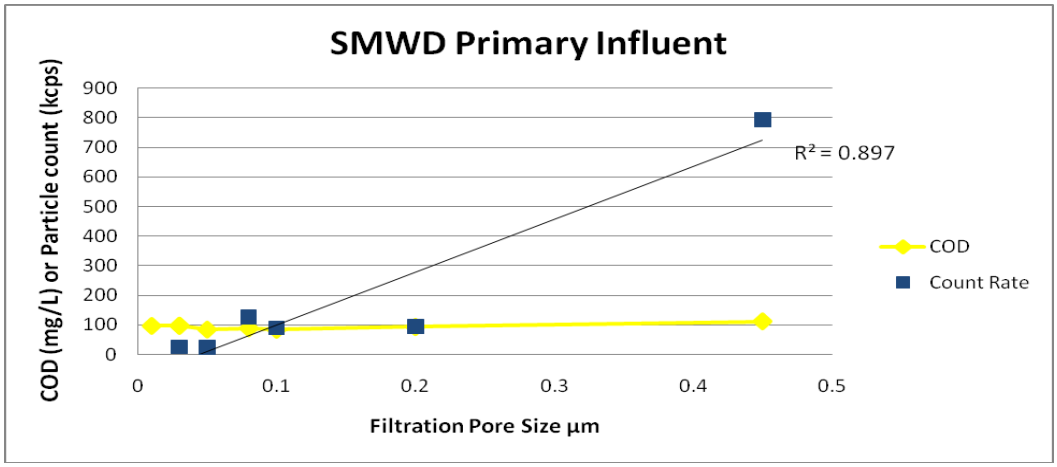

Figure 12: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of SMWD Primary Influent Wastewater

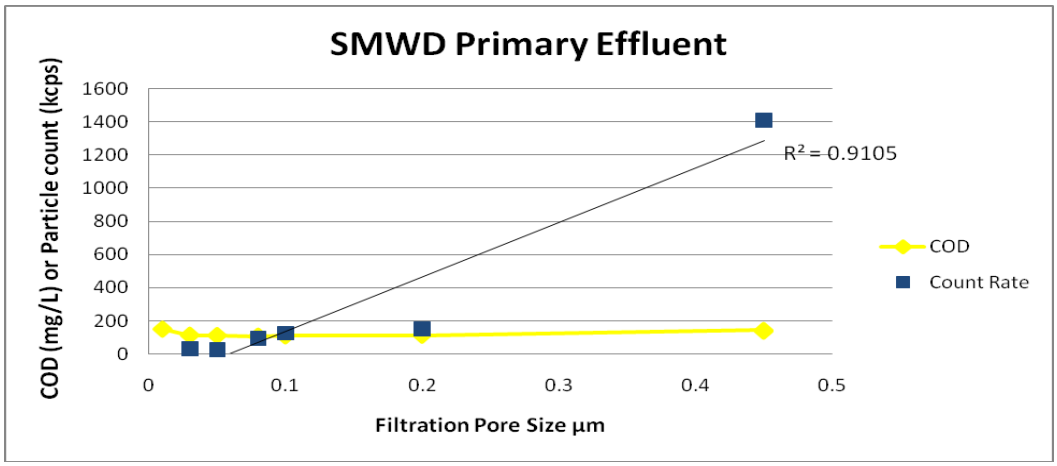

Figure 13: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of SMWD Primary Effluent Wastewater

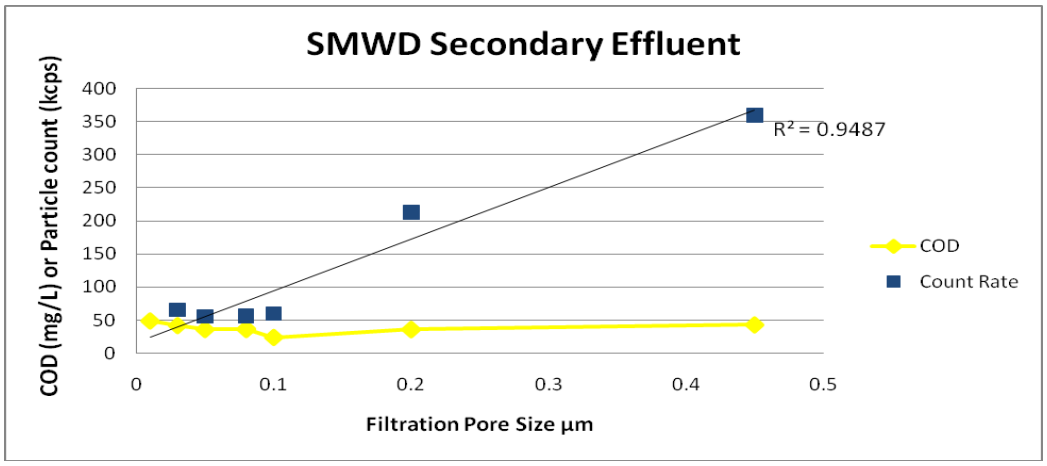

Figure 14: This Figure Relates the Filtration Pore Size (in Micrometers) to the Count Rate and sCOD of SMWD Secondary Effluent Wastewater

3.1.4 Particle Removal through the Treatment Process

Figures 15, 16 and 17 show relatively how many particles are removed for each treatment plant after the secondary treatment process at each filtration step compared to the number of particles in the primary influent sample. OCSD (figure 15) shows more than 50 percent removal of up to 80 nm particles but particles smaller than 50 nm shows no removal. IRWD (figure 16) shows significant removal of nanoscale particles at almost all size ranges. This agrees with previous results where an activated sludge process with a higher MCRT has noticeably higher removal of nanomaterial. SMWD (figure 17) shows approximately 50 percent removal at the higher filtration sizes (450, 100, and 80 nm) but at smaller size ranges (200, 50 and 30nm) there is a production of nanomaterial. Although a higher MCRT appears to have better removal of nanoparticles, process limitations may prevent an increase in MCRT. In any case, process operations at very long MCRT are energy intensive due to the elevated oxygen requirements for endogenous respiration of the biomass, and in general are avoided to limit energy usage.

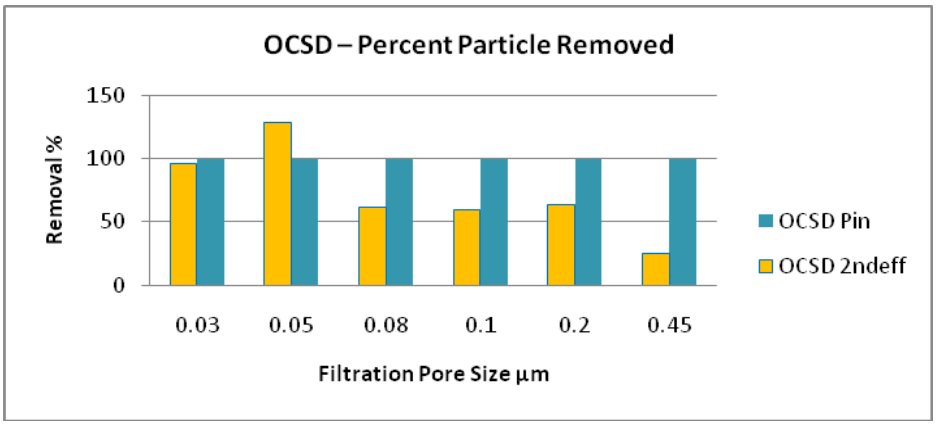

Figure 15: Removal of Particles at OCSD's Secondary Effluent Sample Relative to the Number of Particles in the Primary Influent Sample

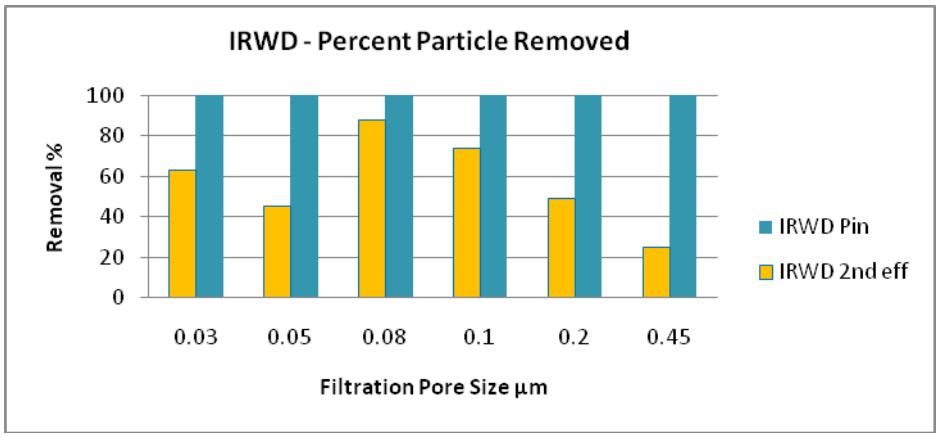

Figure 16: Removal of Particles at IRWD's Secondary Effluent Sample Relative to the Number of Particles in the Primary Influent Sample

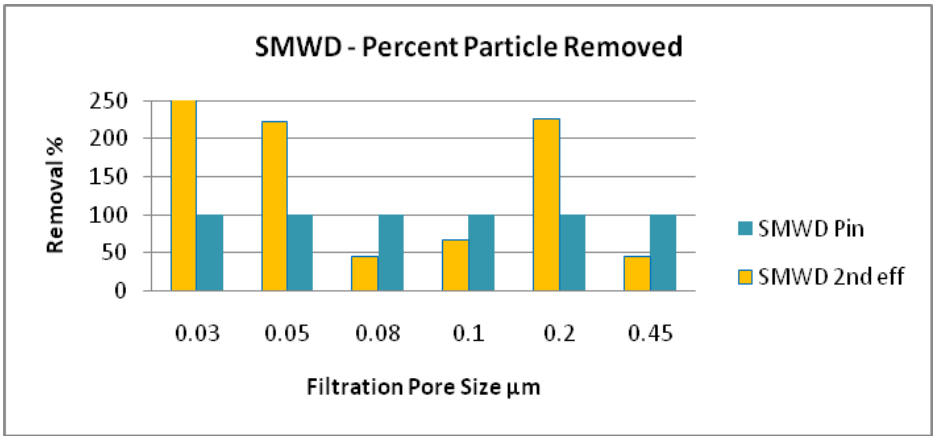

Figure 17: Removal of Particles at SMWD's Secondary Effluent Sample Relative to the Number of Particles in the Primary Influent Sample

3.1.5 Comparison Nanomaterial within Treatment Plants

Figures 18, 19, and 20 presents a relationship between the three treatment plants at each sampling point. Primary influent and effluent samples show similar results for all treatment plants likely due to similar process. However the secondary treatment process differs for each treatment plant so it was expected that the results differ. At the higher filtration sizes (450 and 200 nm) SMWD has many more particles compared to the other plants. This again suggests that the trickling filter process may promote shedding of the nanoscale particles. IRWD is shown to have fewer particles than the other treatment plants and, as discussed before, this may be due to a higher MCRT.

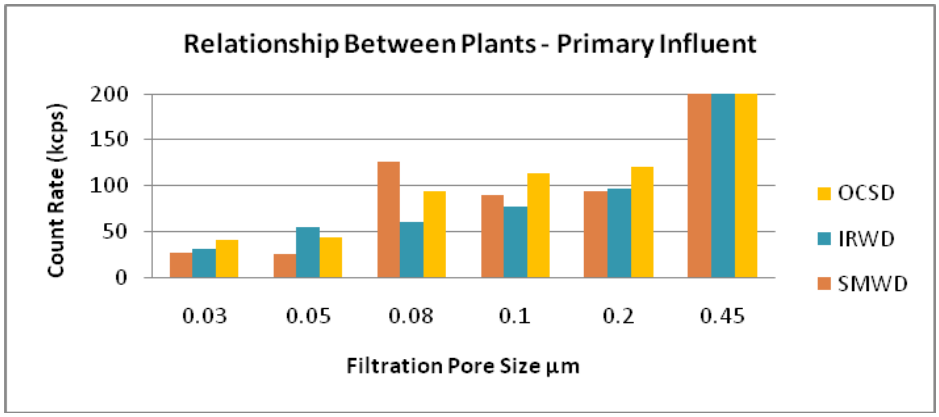

Figure 18: Comparison of the Number of Particles in the Primary Influent Samples of all Three Treatment Plants at Each Filtration Step

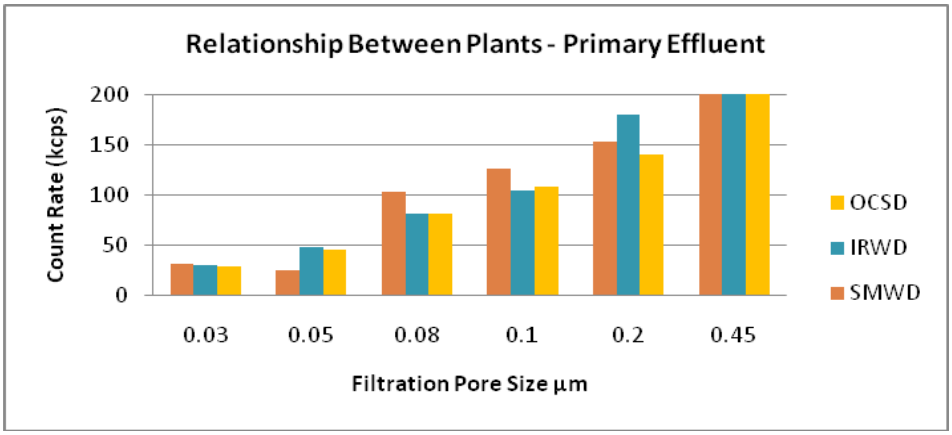

Figure 19: Comparison of the Number of Particles in the Primary Effluent Samples of all Three Treatment Plants at Each Filtration Step

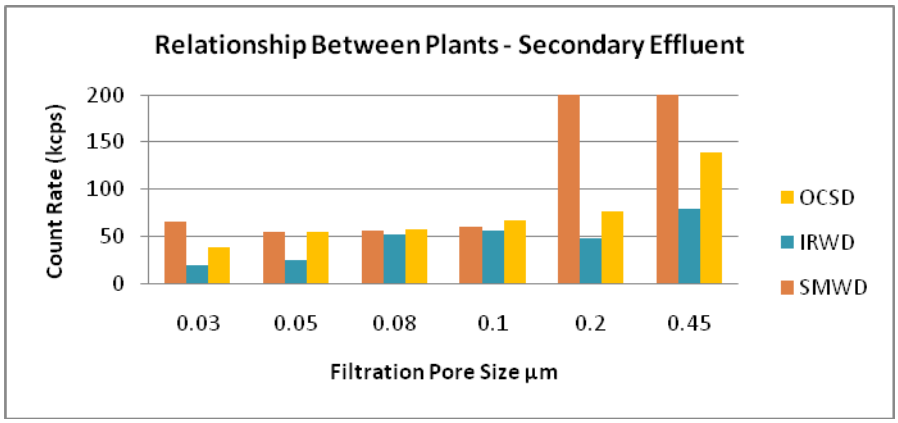

Figure 20: Comparison of the Number of Particles in the Secondary Effluent Samples of all Three Treatment Plants at Each filtration Step

3.2 Potential Impact of Nanoscale Material on Flux in Select Filtration Membranes

This experiment develops a relationship between nanoparticle size and membrane type. Secondary effluent samples from the three treatment plants was filtered and run through flux experiments using hollow MF and UF fibers. The feed and permeate samples were analyzed for particle size distribution.

3.2.1 Flux Analysis of Polypropylene Membranes

The following sections discuss the reduction of flux in polypropylene membranes due to varying sizes of nanomaterial and analysis of the feed and permeate samples.

3.2.1.1 Flux Reduction Results

The flux results are shown in figures 21 through 23. This setup is kept at constant pressure so a decrease in flux represents membrane fouling due to either pore clogging or cake formation. As expected the change of flux due to fouling decreases as the pre filtered size decreases. However, there are only slight differences in the flux reduction between the unfiltered and 100 nm filtered samples. This shows that particles as small as 100 nm can potentially contribute significantly to the fouling of polypropylene membranes. Samples filtered to 3.5 nm appear to contribute to as much as 50 percent of the fouling while 2.5 nm particles do not appear to affect the flux as dramatically.

The largest amount of fouling generally occurs within the first five minutes. This is likely due to small particles (<200nm) being trapped within pores of the membranes. Then after five minutes a majority of the pores are clogged with particles. This forces particles remaining in solution to form a cake layer on the outside of the membrane further reducing the flow through the membrane. Pre-filtered 2.5 and 3.5 nm samples only show fouling in the first few minutes which is indicative of pore clogging. After this point, the flux appears to stabilize which shows these particles are too small to significantly contribute to cake formation. This is discussed further in the next section with PVDF membranes.

When comparing the three plants IRWD is shown to have the slowest reduction in flux for all the samples tested. This is likely due to fewer particles seen in the secondary treated water, which is also discussed in task 1 results. SMWD samples were found to foul more rapidly compared to other treatment plants samples. This is due to the higher number of particles after the secondary treatment (trickling filtration). This is also discussed in the results found in task 1.

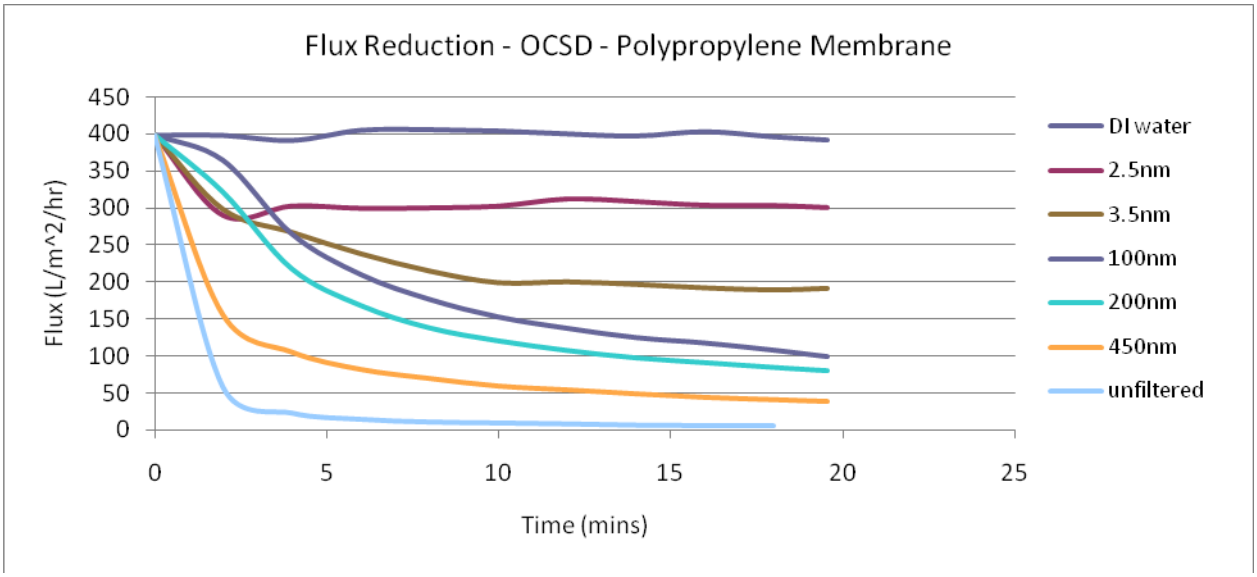

Figure 21: The Reduction of Flux Through Polypropylene Membranes Using Select Pre-Filtration Sizes of OCSD Secondary Effluent

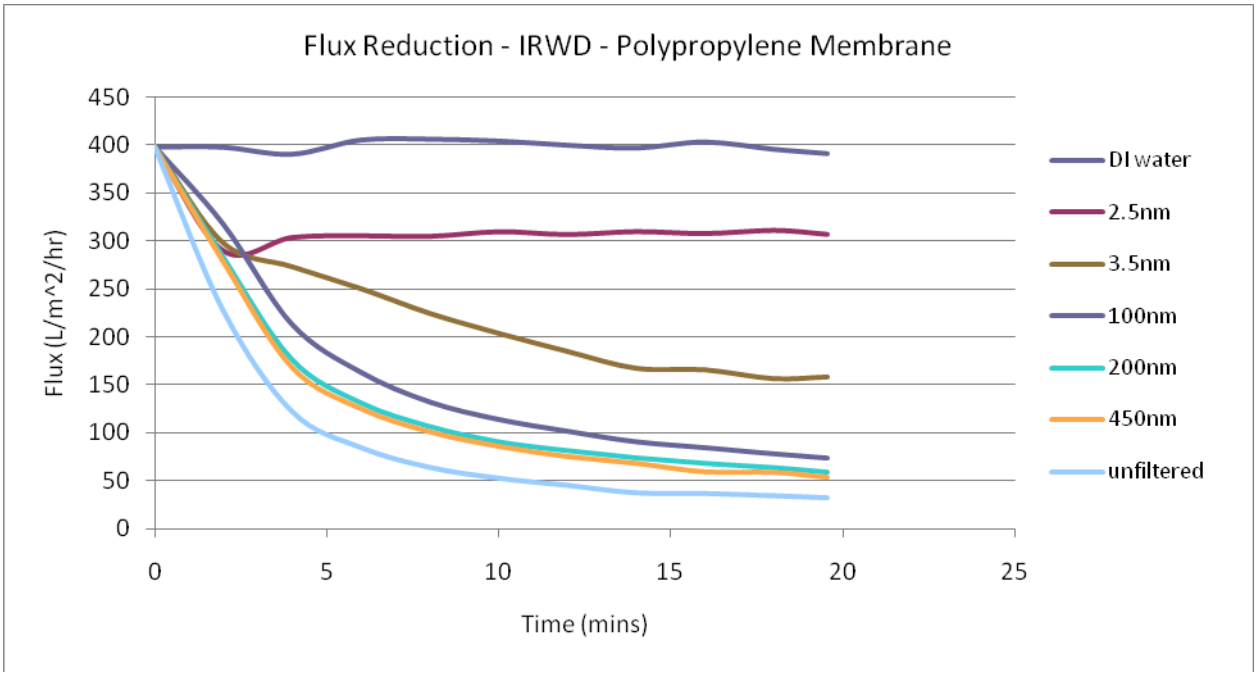

Figure 22: The Reduction of Flux Through Polypropylene Membranes Using Select Pre-Filtration Sizes of IRWD Secondary Effluent

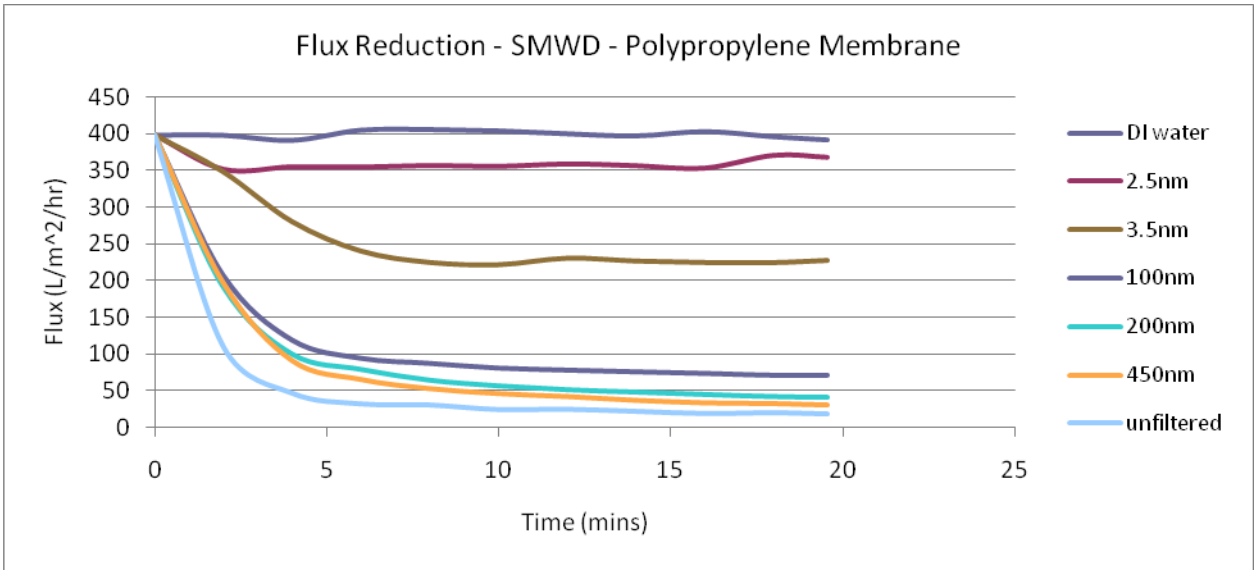

Figure 23: The Reduction of Flux Through Polypropylene Membranes Using Select Pre-Filtration Sizes of SMWD Secondary Effluent

3.2.1.2 Particle Analysis of Flux Experiments

Figures 24, 25 and 26 show the number of particles within the feed and permeate samples used for the flux analysis. Due to pre filtration the number of particles in the feed samples gradually decreases from the unfiltered sample to 100nm. The 3.5 and 2.5 nm filtered samples vary because very few particles are in the sample and this makes it difficult for the instrument to accurately analyze. In addition, contamination by dust particles is very common for this instrument. The permeate particle count is usually found to be fewer than the amount seen in the feed sample but it does not follow a trend and appears to be dependent on the integrity of the membrane. It is possible that the membrane may shed particles due to the filtration process.

Figures 27, 28, and 29 show the average particle size within the feed and permeate samples. As seen with the count rate the size generally decreases gradually between the unfiltered and 100 nm pre-filtered samples. Permeate sample vary significantly due to either contamination by dust or problems with the instrument as discussed above.

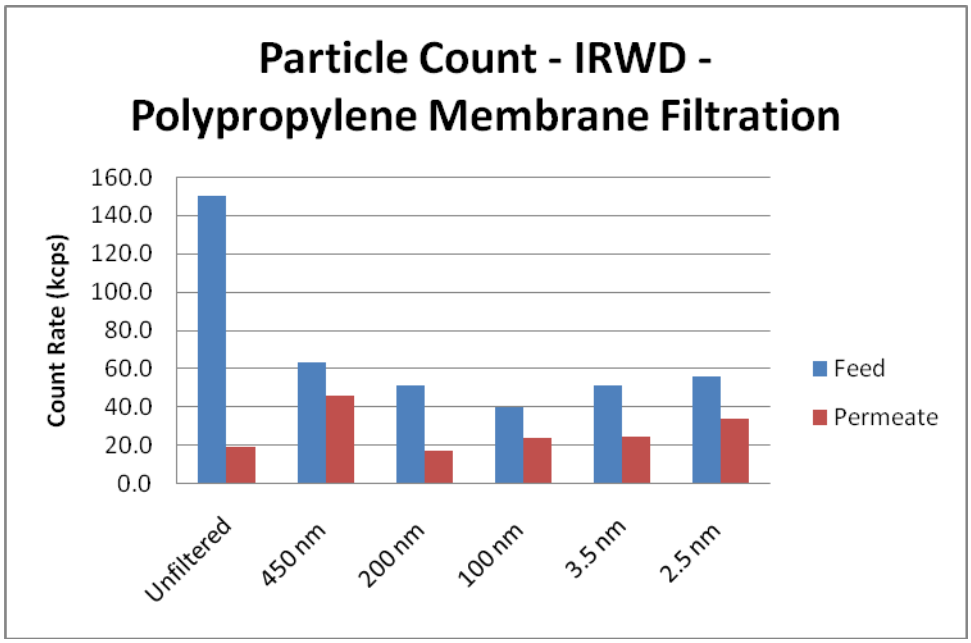

Figure 24: Photon Count Rate (kcps) Measured as a Surrogate to Particles Count in Feed and Permeate Samples Using Polypropylene Hollow Fiber Membranes With Select Filtration Sizes of IRWD Secondary Effluent

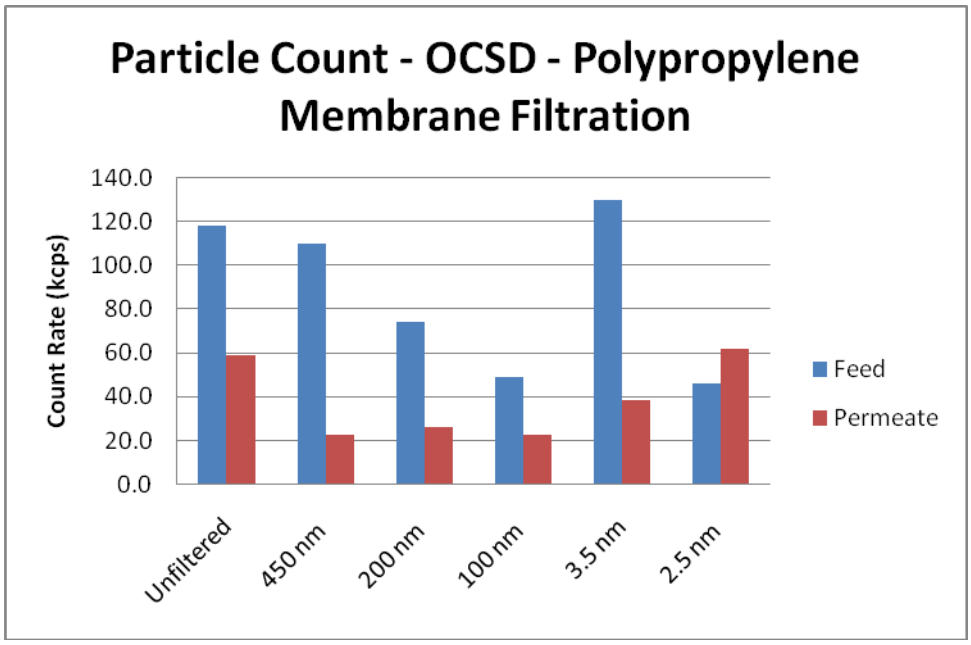

Figure 25: Photon Count Rate (kcps) Measured as a Surrogate to Particles Count in Feed and Permeate Samples Using Polypropylene Hollow Fiber Membranes With Select Filtration Sizes of OCSD Secondary Effluent

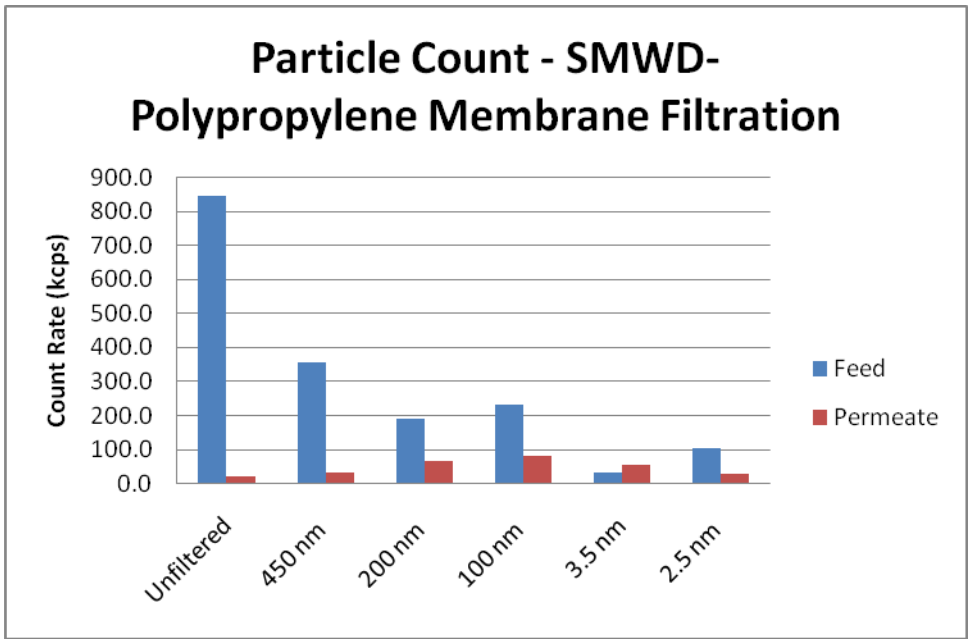

Figure 26: Photon Count Rate (kcps) Measured as a Surrogate to Particles Count in Feed and Permeate Samples Using Polypropylene Hollow Fiber Membranes With Select Filtration Sizes of SMWD Secondary Effluent

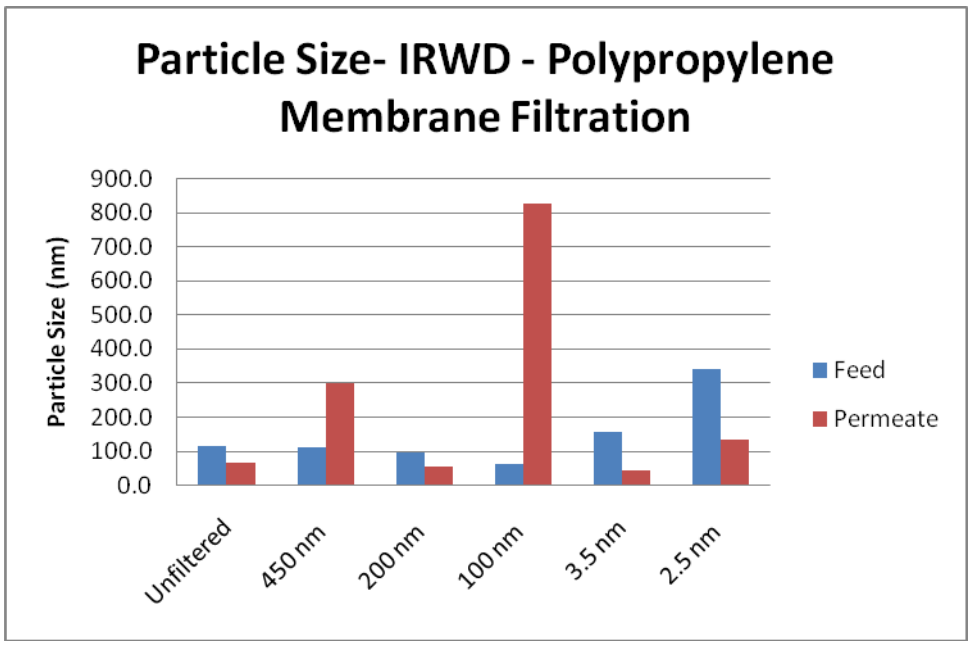

Figure 27: Particle Size Measured in Feed and Permeate Samples Using Polypropylene Hollow Fiber Membranes With Select Filtration Sizes of IRWD Secondary Effluent

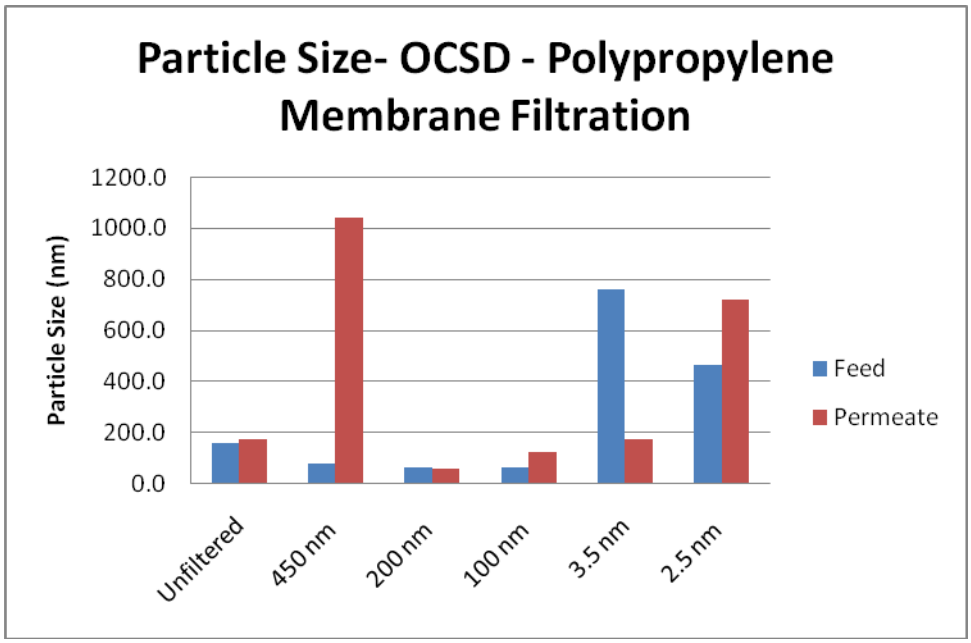

Figure 28: Particle Size Measured in Feed and Permeate Samples Using Polypropylene Hollow Fiber Membranes With Select Filtration Sizes of OCSD Secondary Effluent

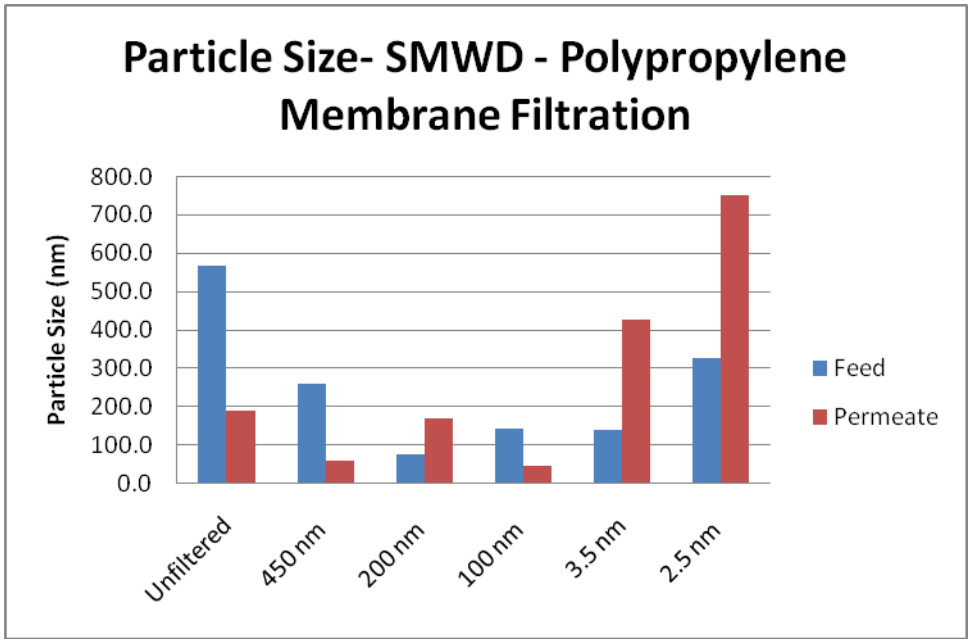

Figure 29: Particle Size Measured in Feed and Permeate Samples Using Polypropylene Hollow Fiber Membranes With Select Filtration Sizes of SMWD Secondary Effluent

3.2.2 Flux Analysis of PVDF Membranes

The following sections discuss the reduction of flux in PVDF membranes due to varying sizes of nanomaterial and analysis of the feed and permeate samples.

3.2.2.1 Flux Reduction Results

The flux results for PVDF1 membranes are shown in figures 30 through 32. All samples generally varied between 50 and 30 L/m^2/hr but it was found that the flow rate is based on the integrity of the specific membrane used for each individual sample. Due to this all results are normalized with respect to DI water which was run through each membrane prior to each sample. There may be discrepancies in the data where the flux is increasing. This is because the membranes are not at steady state conditions and during start up the membrane pores may have opened up slightly during the experimental runs. Flux experiments with PVDF2 are seen in figure 33. Due to time constraints only SMWD secondary effluent was tested with this membrane because it was found to have the mort particles (see task 1). Again, all results are normalized with DI water but the flow rate for individual samples varies between 70 and 20 L/m^2/hr.

According to figures 30 through 32 (PVDF1) the same trend is seen in polypropylene membranes where samples with larger particles foul the membrane more rapidly. However, PVDF1 membranes do not foul the same as polypropylene. Most samples that foul the PVDF1 membranes show a gradual decline in flux through the entire run. Since, PVDF1 membranes have a significantly smaller pore size (40 nm) compared to polypropylene membranes (200 nm), cake formation is the primary fouling mechanism. Samples with a majority of particles larger than 40 nm will not foul these membranes by pore clogging. However, 3.5 and 2.5 pre filtered samples only show signs of fouling in the first few minutes which is very similar to what was seen with polypropylene membranes. It is likely that particles within these samples initially foul the membrane by pore clogging but then after they have no effect on the membrane flux.

Comparing the three treatment plants the same trends appear as with polypropylene flux results but the differences are very small and insignificant. IRWD is shown to have fouled slightly less due to cleaner treated water and SMWD is shown to have fouled slightly more due to more particles in the secondary treated water.

Figure 33 shows the flux reduction results using PVDF2. This membrane does not appear to foul the same as the previous PVDF membrane. This fouling mechanism appears to relate more to polypropylene membranes where the largest decline in flux occurs within the first few minutes of the run. This may be due to the setup since this particular membrane did not thread well onto any needle it was epoxy glued onto the needle. It is possible the integrity of the membrane may be compromised. Another possibility, as discusses above, the fiber used in this experiment are run during startup conditions and may need to ripen in order to attain the nominal pore size. In any case, the results show that particles clog many of the pores within the first 10 minutes then fouling becomes more gradual indicating the formation of a cake layer.

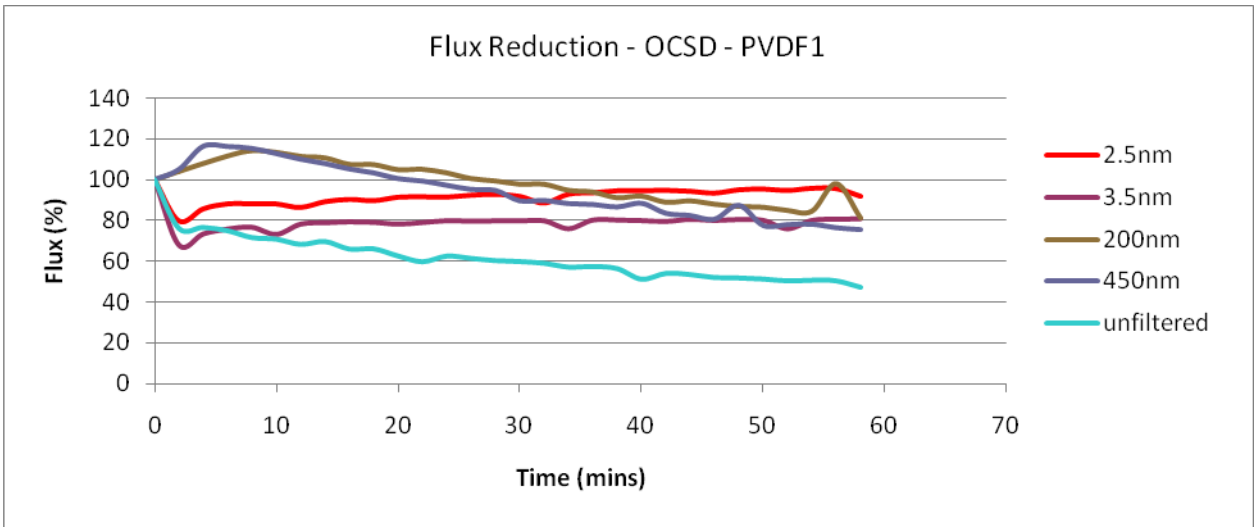

Figure 30: The Reduct Flux Through PVDF1 Membranes Using Select Pre-Filtration Sizes of OCSD Secondary Effluent

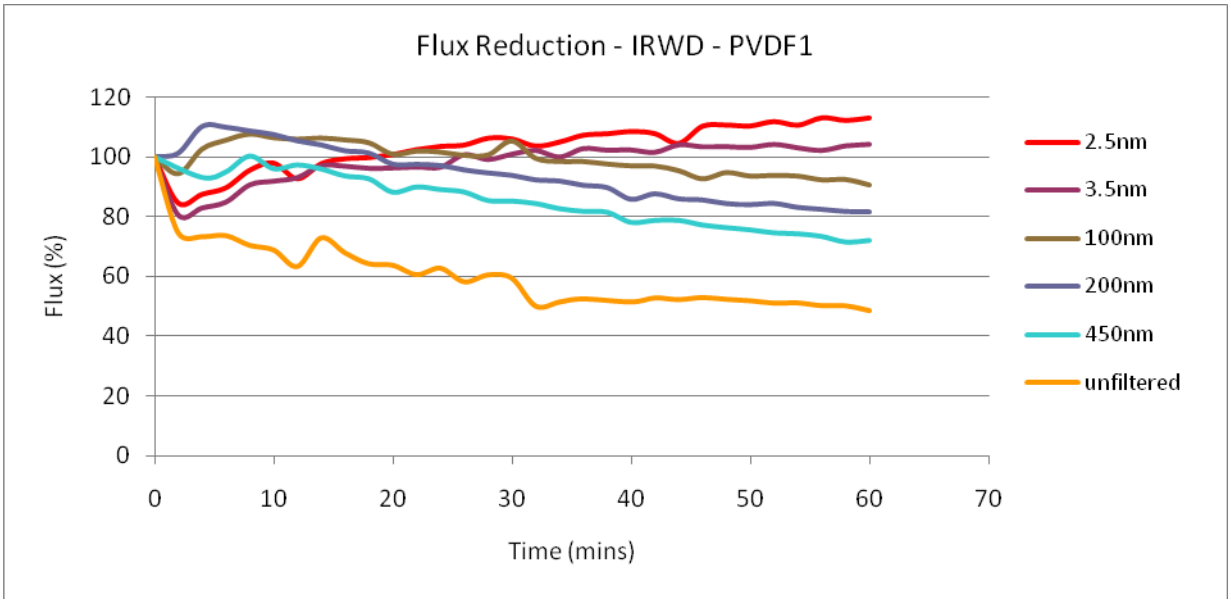

Figure 31: The Reduction of Flux Through PVDF1 Membranes Using Select Pre-Filtration Sizes of IRWD Secondary Effluent

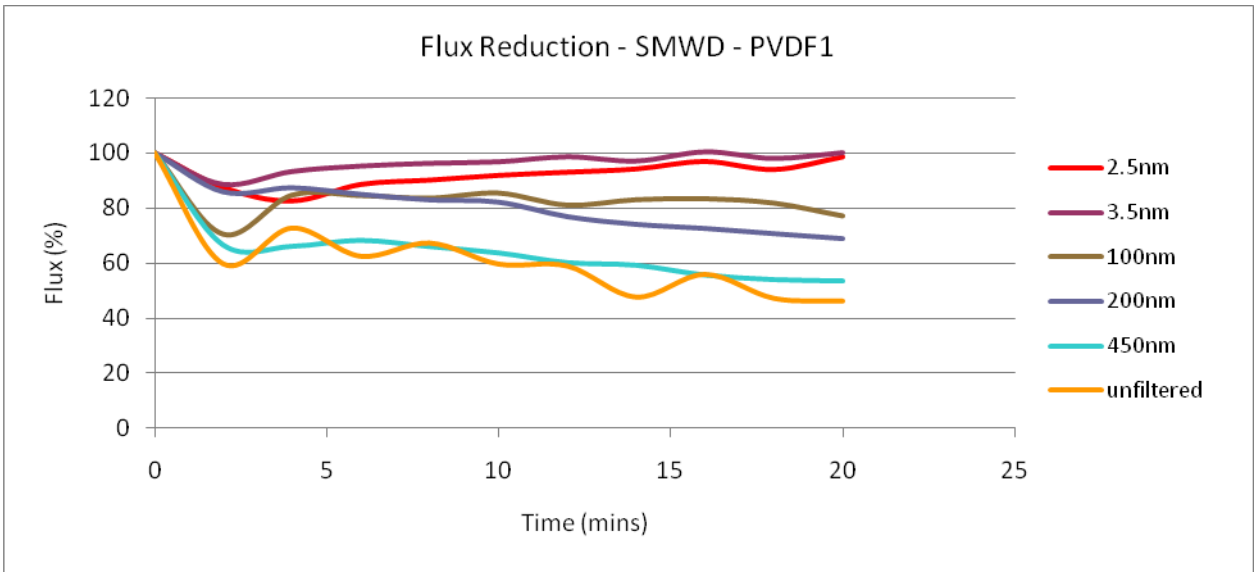

Figure 32: The Reduction of Flux Through PVDF1 Membranes Using Select Pre-Filtration Sizes of SMWD Secondary Effluent

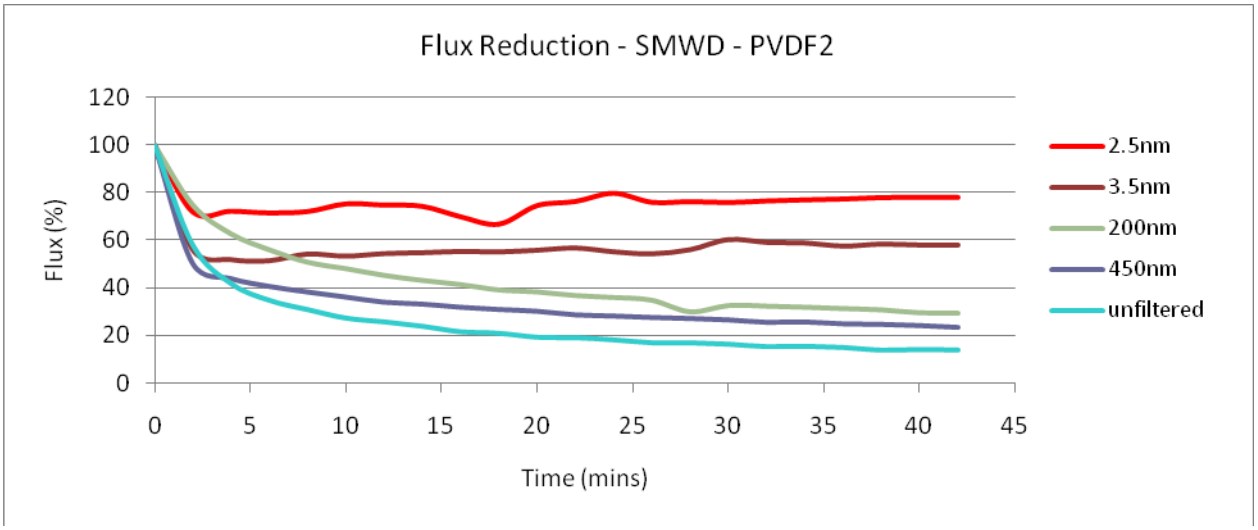

Figure 33: The Reduction of Flux Through PVDF2 Membranes Using Select Pre-Filtration Sizes of SMWD Secondary Effluent

3.2.2.2 Particle Analysis of Flux Experiments

Figures 34 through 37 show the number of particles within the feed and permeate samples used for PVDF flux analysis. As discussed in the previous section, the number of particles in the feed samples gradually decreases from the unfiltered sample to 100nm. Particle count in the permeate samples do not follow a trend and appear to be dependent on the integrity of the membrane. Also, permeate particle count is usually found to be fewer than the amount seen in the feed sample.

Figures 38 and 41 show the average particle size within the feed and permeate samples. As seen with the count rate the size generally decreases gradually between the unfiltered and 100 nm pre-filtered samples. Permeate samples vary significantly due to either contamination by dust or problems with the instrument.

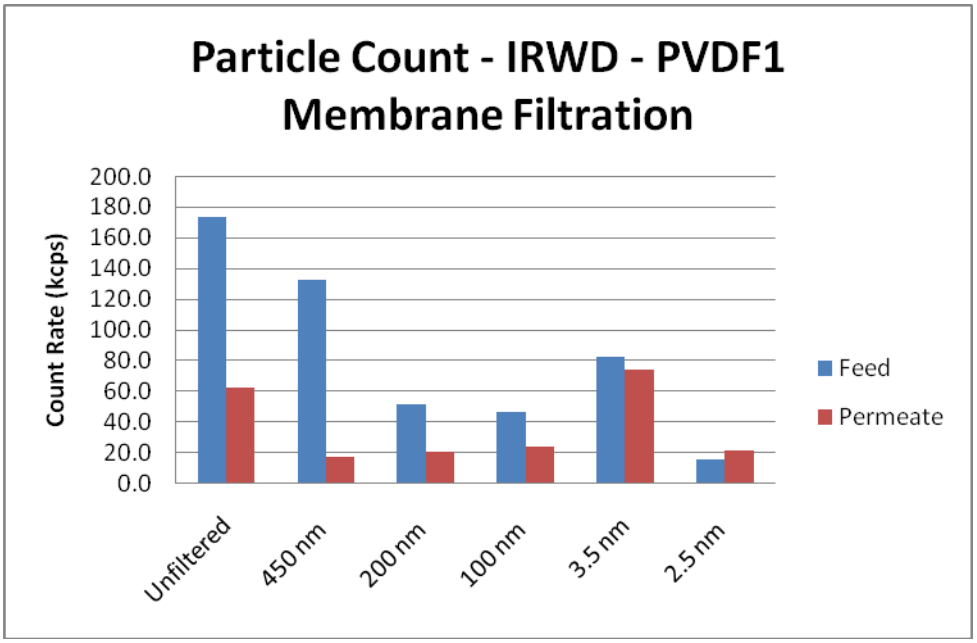

Figure 34: Photon Count Rate (kcps) Measured as a Surrogate to Particles Count in Feed and Permeate Samples Using PVDF1 Hollow Fiber Membranes With Select Filtration Sizes of IRWD Secondary Effluent

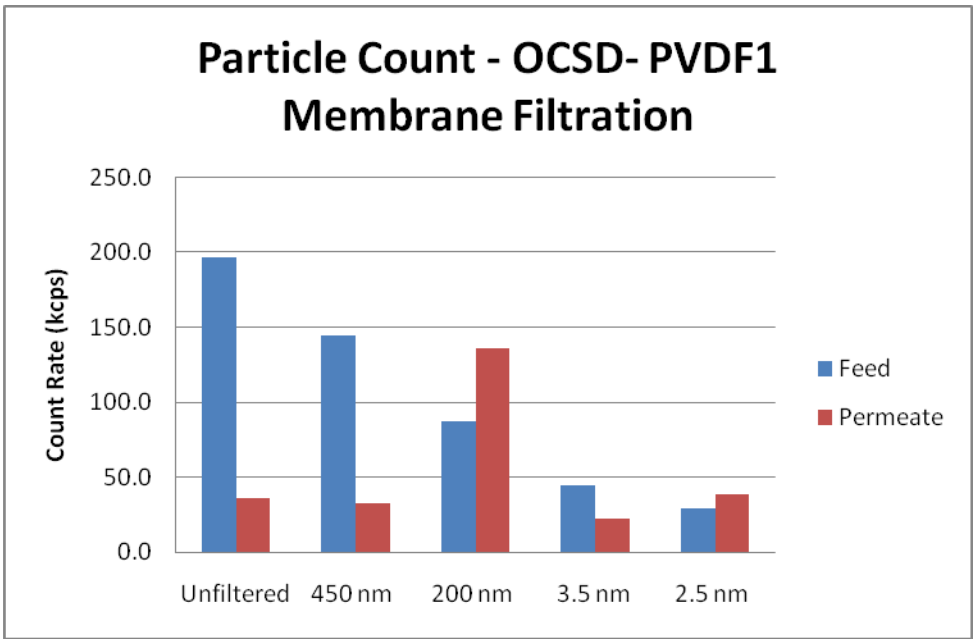

Figure 35: Photon Count Rate (kcps) Measured as a Surrogate to Particles Count in Feed and Permeate Samples Using PVDF1 Hollow Fiber Membranes With Select Filtration Sizes of OCSD Secondary Effluent

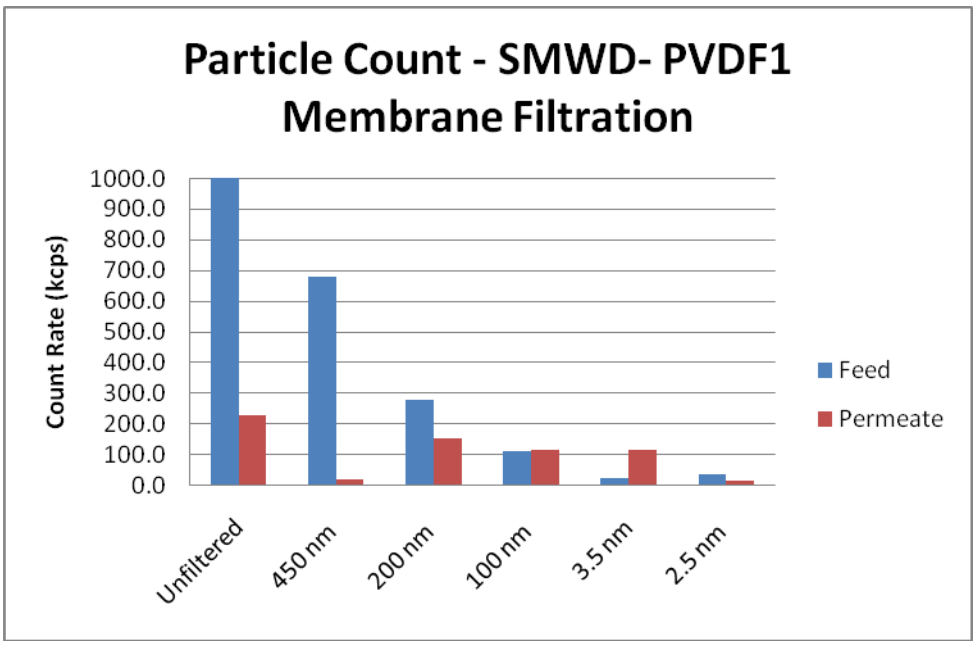

Figure 36: Photon Count Rate (kcps) Measured as a Surrogate to Particles Count in Feed and Permeate Samples Using PVDF1 Hollow Fiber Membranes With Select Filtration Sizes of SMWD Secondary Effluent

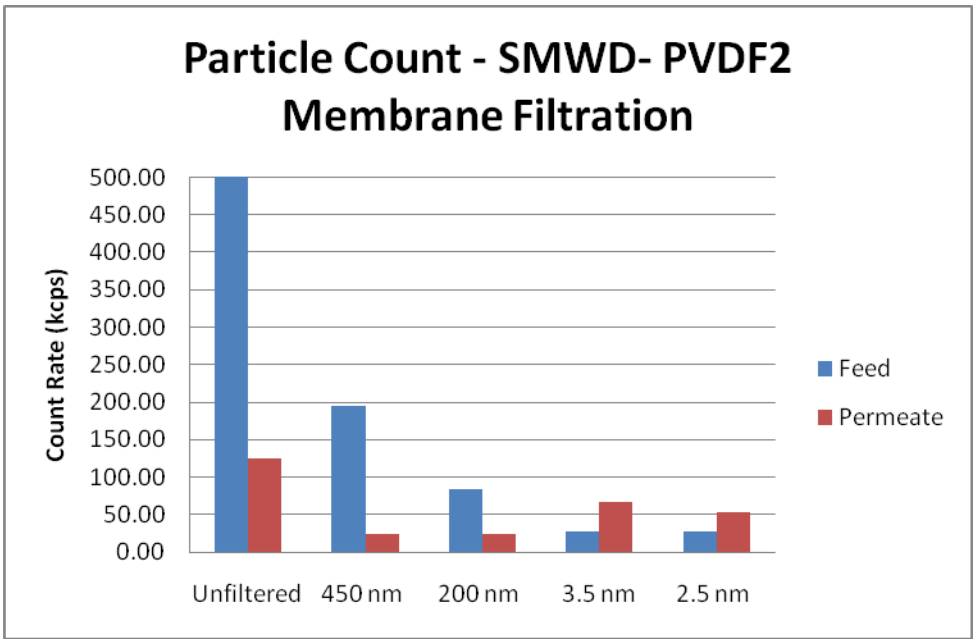

Figure 37: Photon Count Rate (kcps) Measured as a Surrogate to Particles Count in Feed and Permeate Samples Using PVDF2 Hollow Fiber Membranes With Select Filtration Sizes of SMWD Secondary Effluent

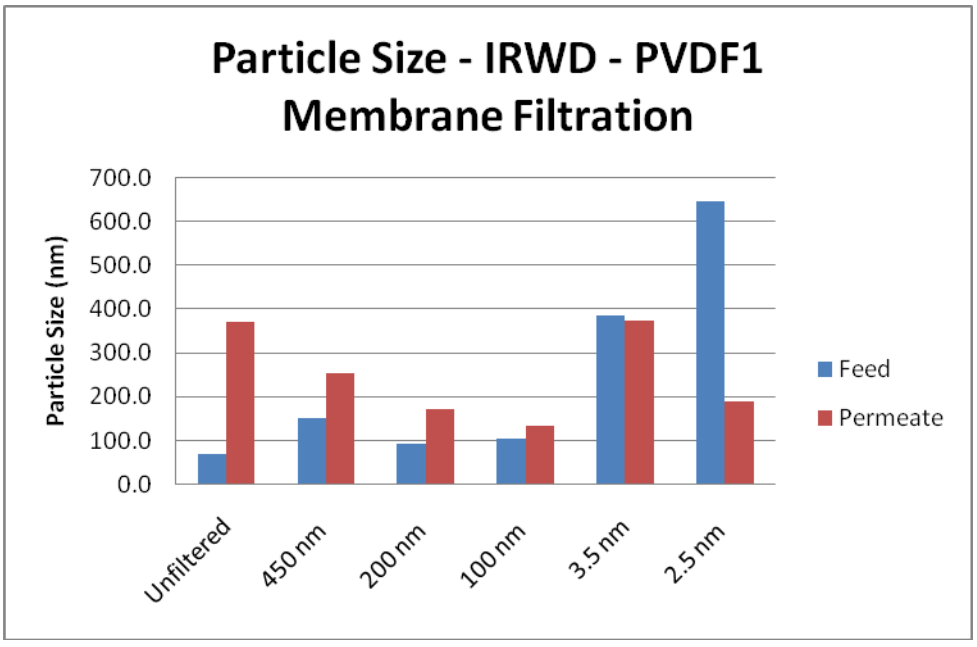

Figure 38: Particle Size Measured in Feed and Permeate Samples Using PVDF1 Hollow Fiber Membranes With Select Filtration Sizes of IRWD Secondary Effluent

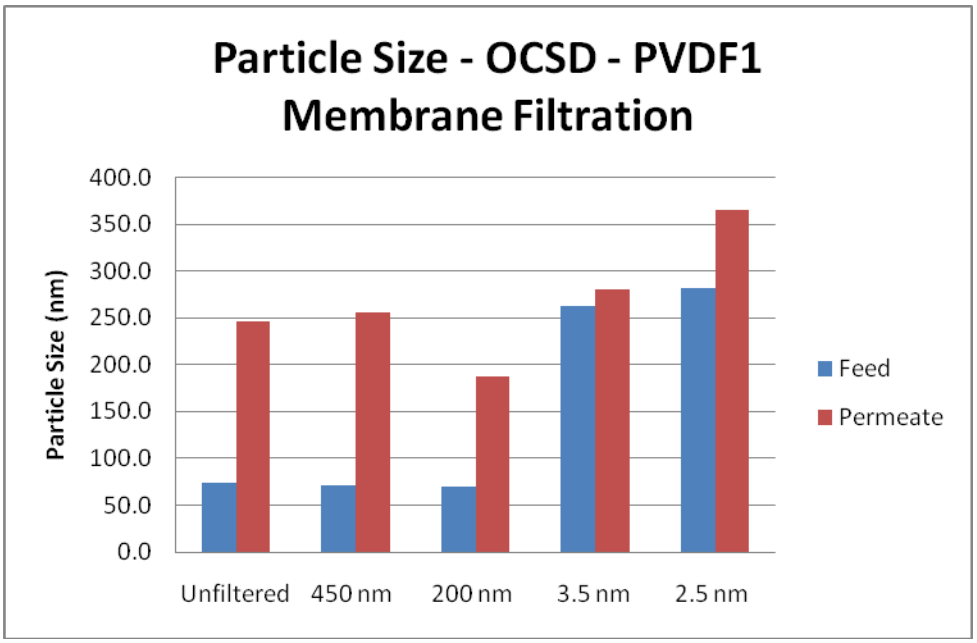

Figure 39: Particle Size Measured in Feed and Permeate Samples Using PVDF1 Hollow Fiber Membranes With Select Filtration Sizes of OCSD Secondary Effluent

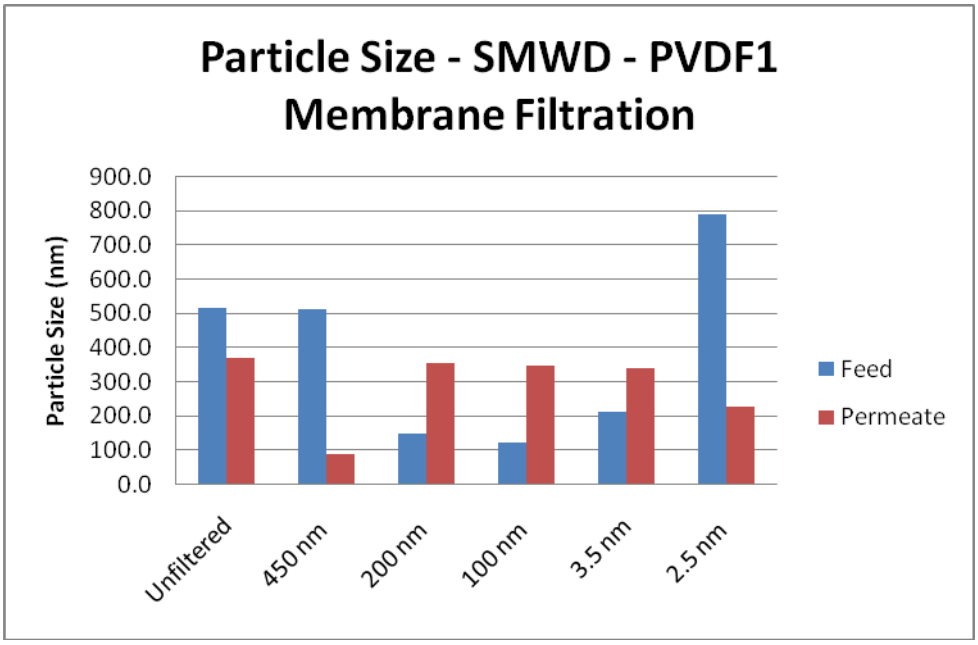

Figure 40: Particle Size Measured in Feed and Permeate Samples Using PVDF1 Hollow Fiber Membranes With Select Filtration Sizes of SMWD Secondary Effluent

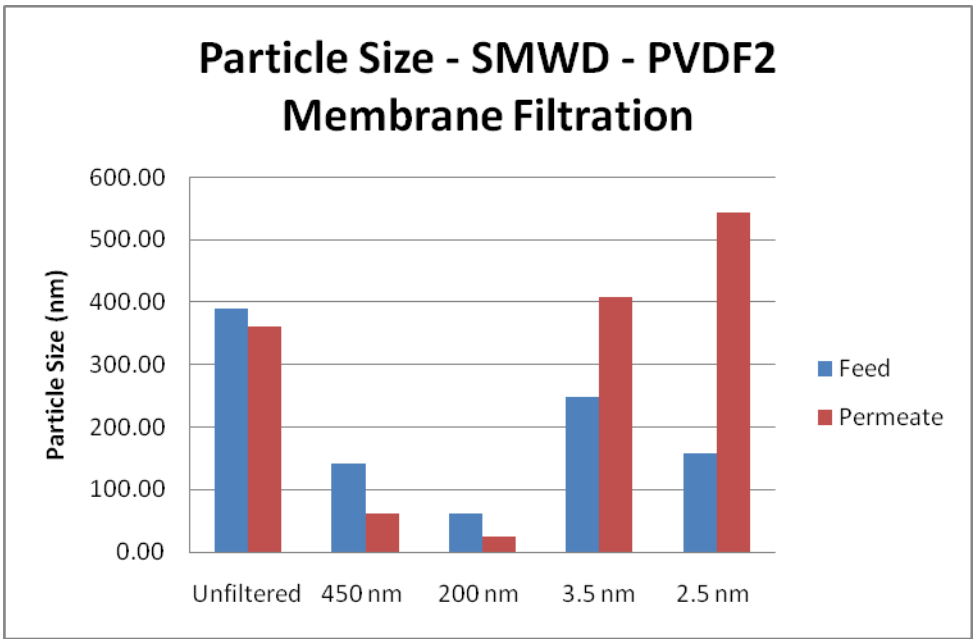

Figure 41: Particle Size Measured in Feed and Permeate Samples Using PVDF2 Hollow Fiber Membranes With Select Filtration Sizes of SMWD Secondary Effluent

3.3 Pretreatment for Removal of Nanoscale Suspended Particles

This section discusses the removal of nanoscale particles using coagulation/precipitation techniques and potential improvements using flux reduction experiments.

3.3.1 Nanoparticle Removal with Coagulant Pre-Treatment

Select concentrations of alum, ferric chloride, or polymer were added to SMWD secondary treated wastewater to determine the removal of nanoparticles. Analysis for sCOD is shown in figures 42 and 43. Particle analyses of the samples are shown in figures 44 through 47. Generally, all the coagulants show very similar trends at similar coagulant concentrations and no one coagulant appears to stand out significantly. Ferric chloride and alum appear to lower the sCOD and turbidity slightly more than the polymer at equivalent concentrations but not by a significant amount. Overall, there is a 70 – 80 percent removal of nanoparticles between the highest coagulant dose and the untreated sample. The count rate shows similar results for the polymer and ferric chloride. However, alum appears to vary in the unfiltered and filtered samples. In the unfiltered results the alum appears to remove fewer particles compared to other coagulants at similar coagulant concentrations. However, in the filtered results it appears that the alum removes these particles noticeably better than the other coagulants. It seems alum is able to coagulate smaller particles better than others but many of the particles do not become big enough to readily settle out of solution compared to the other coagulants at higher concentrations.

In terms of particle size (figures 46 and 47) it is difficult to see a clear trend in every sample. Generally, it appears the particle size increases with increasing coagulant concentration. Some result show particle sizes increasing up to about 50 mg/l concentration but then stabilizes or decreases in size. This shows particles are agglomerating and increasing in size but at a certain

coagulant concentration the particles become big enough to settle out of solution which would not add to the results.

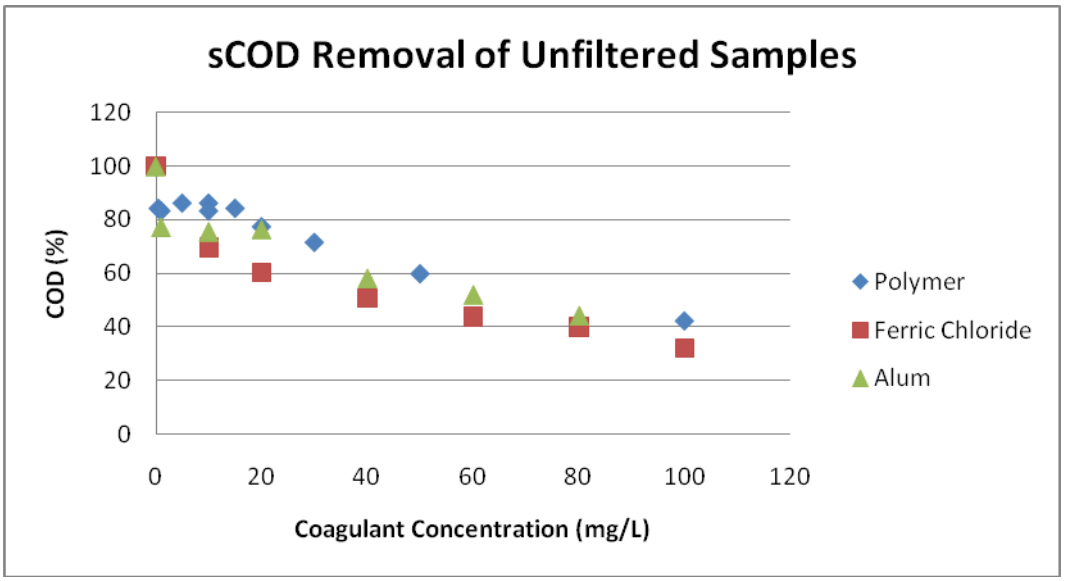

Figure 42: Relation Between the Concentration of the Coagulant to the Relative sCOD Removal for the Polymer, Ferric Chloride, and Alum of Unfiltered Samples

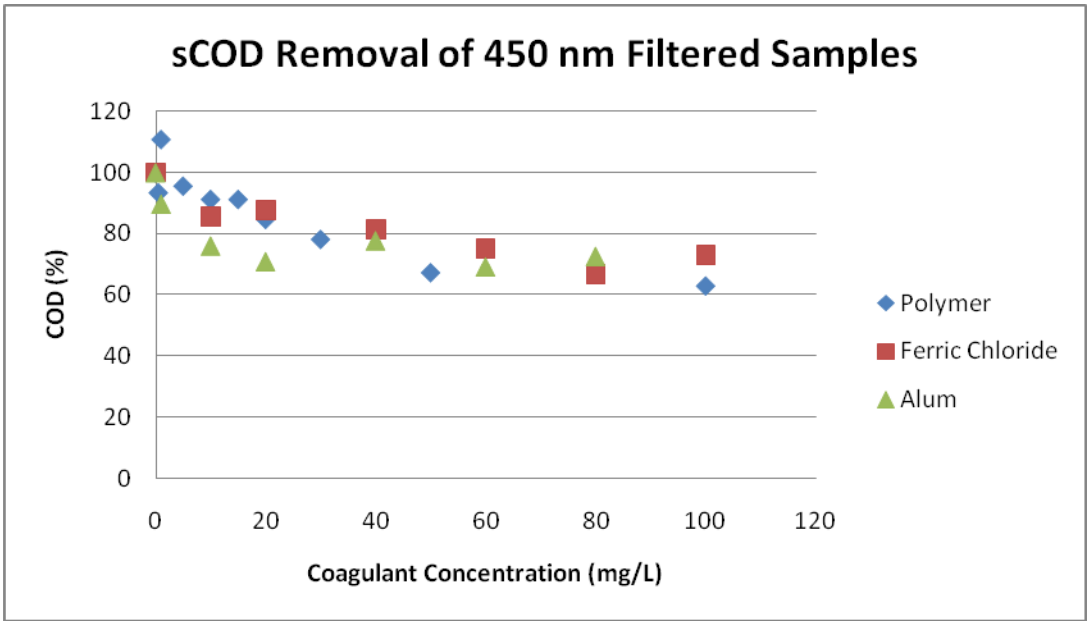

Figure 43: Relation Between the Concentration of the Coagulant to the Relative sCOD Removal for the Polymer, Ferric Chloride, and Alum of 450 nm Filtered samples

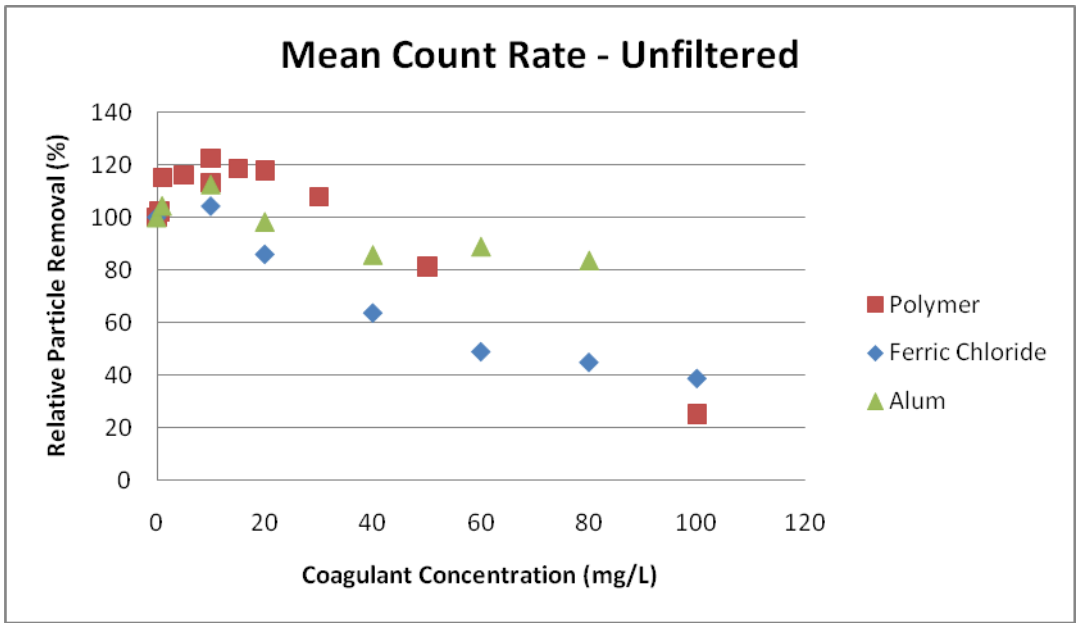

Figure 44: Relation Between the Concentration of the Coagulant to the Relative Number of Particles (kcps) Removed by the Polymer, Ferric Chloride, and Alum of Unfiltered Samples

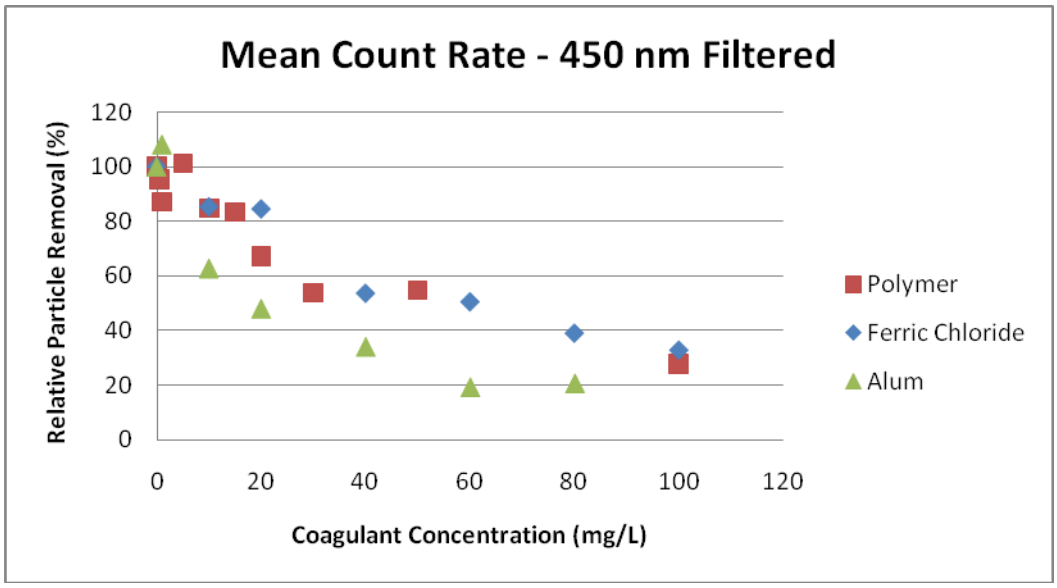

Figure 45: Relation Between the Concentration of the Coagulant to the Relative Number of Particles (kcps) Removed by the Polymer, Ferric Chloride, and Alum of 450nm Filtered Samples

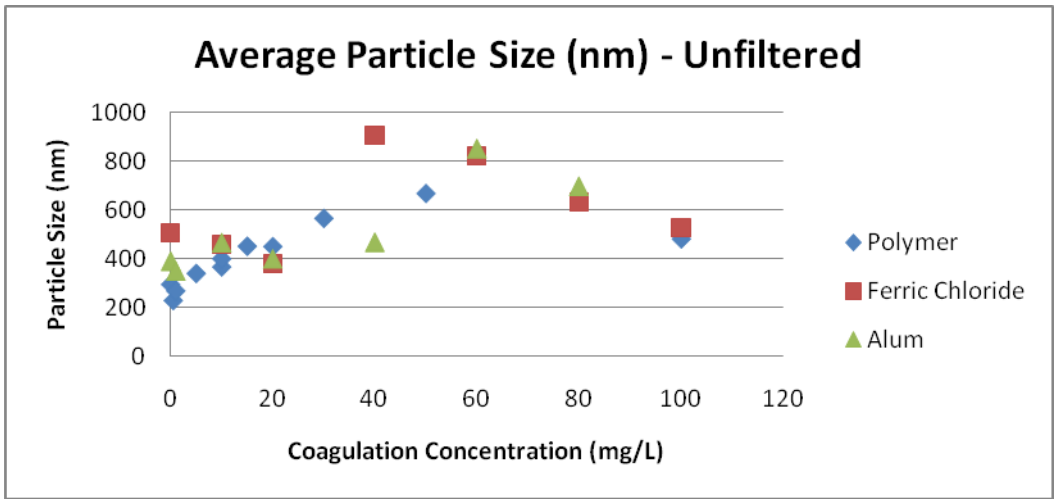

Figure 46: Relation Between the Concentration of the Coagulant to the Particle Size (nm) Remaining in Solution After Treatment With the Polymer, Ferric Chloride, and Alum of Unfiltered Samples

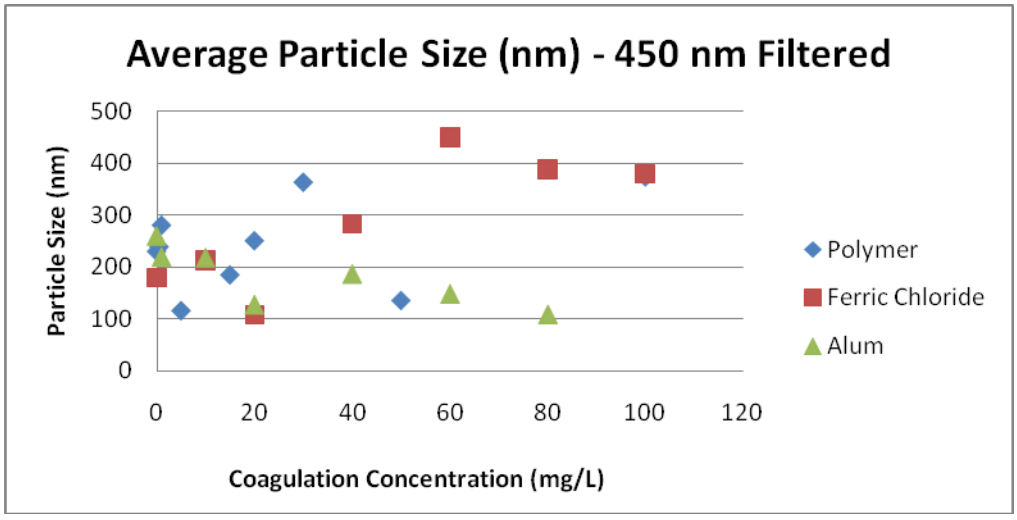

Figure 47: Relation Between the Concentration of the Coagulant to the Particle Size (nm) Remaining in Solution After Treatment With the Polymer, Ferric Chloride, and Alum of 450 nm Filtered Samples

3.3.2 Flux Reduction Analysis with Pre-Treated Wastewater

After pre-treatment with one of the three coagulants (alum, ferric chloride, or the polymer) a sample was taken at select concentrations for flux reduction analysis. Flux analysis was conducted as described in task 2 but with varying concentration of coagulant instead of varying pre-filtered size ranges. Flux results for alum, ferric chloride, and the polymer are shown in figures 48, 49 and 50, respectively. Overall, as seen in the previous section, no single coagulant appears to perform better compared to the others. At similar concentrations each coagulant appears to have similar flux reduction results. The only sample that stands is the highest concentration of the polymer (100mg/L). This sample seems to have been more effective at removing particles from solution allowing for a significantly higher flux rate. This is supported

by the previous section where 100 mg/L concentration of the polymer was found to have the least number of particles.

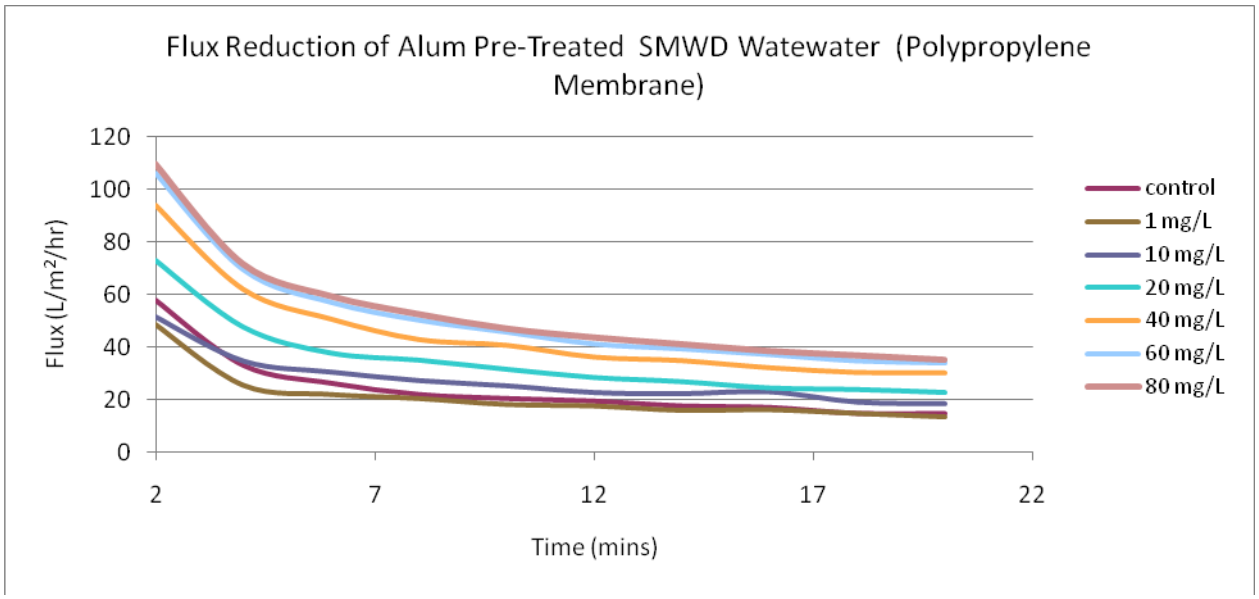

Figure 48: The Reduction of Flux Through Polypropylene Membranes Using Select Pre-Treated Concentrations of Alum in SMWD Secondary Effluent

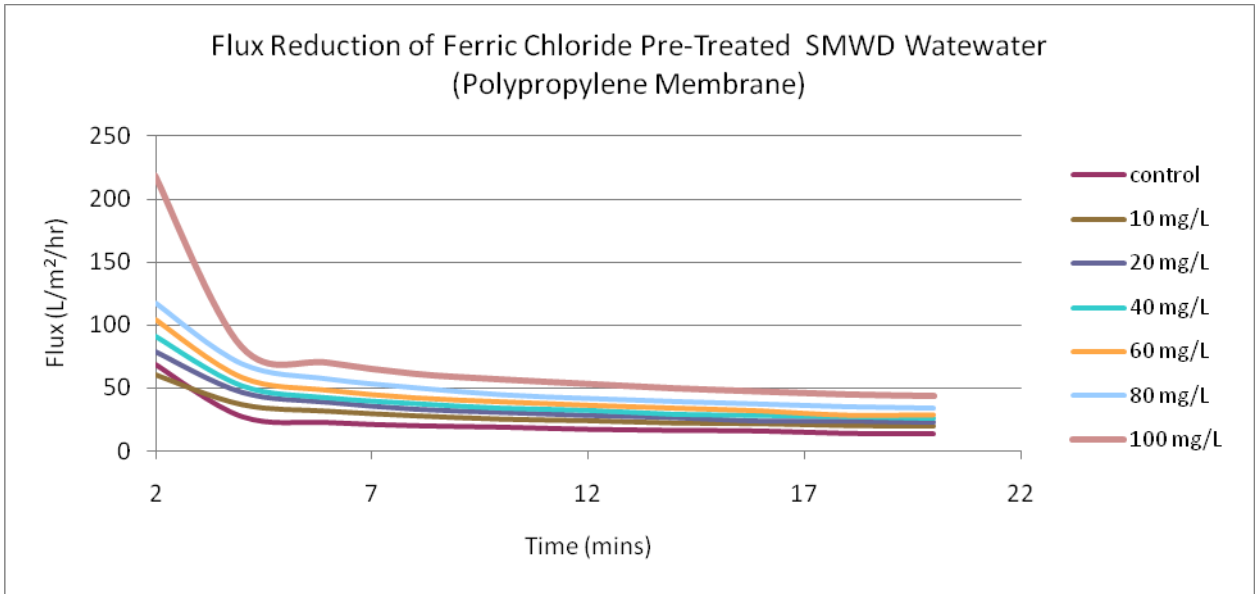

Figure 49: The Reduction of Flux Through Polypropylene Membranes Using Select Pre-Treated Concentrations of Ferric Chloride in SMWD Secondary Effluent

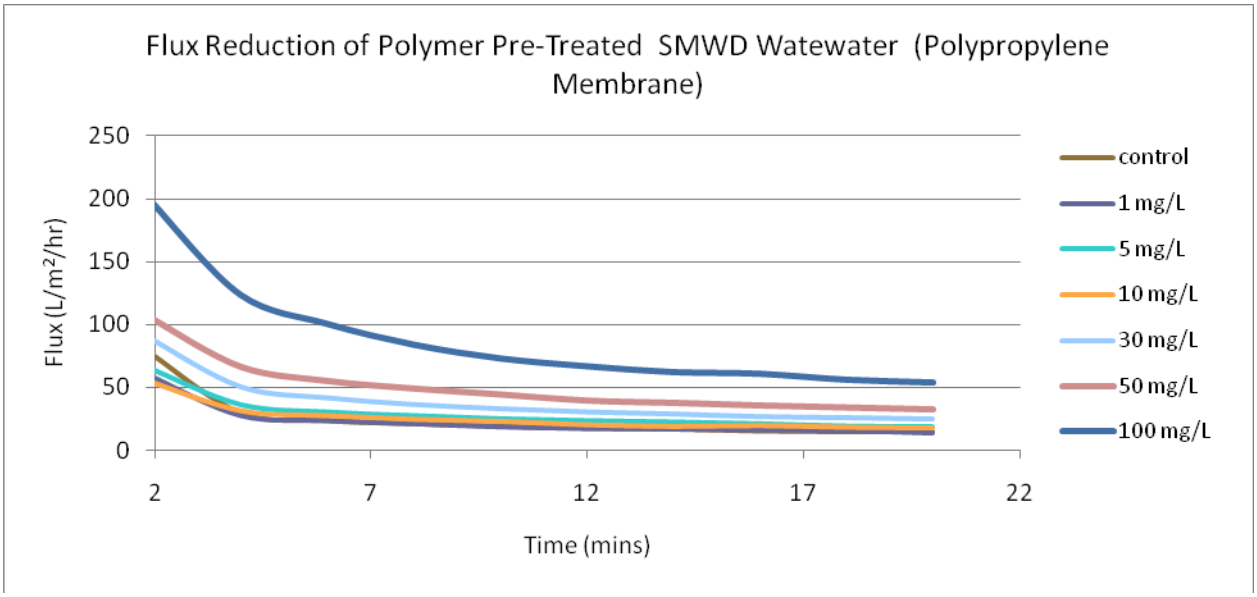

Figure 50: The Reduction of Flux Through Polypropylene Membranes Using Select Pre-Treated Concentrations of the Polymer in SMWD Secondary Effluent

3.4 Estimation of Energy Consumption Due to Nanoscale Suspended Particles

The following sections discuss the energy demand exerted by various size fractions of biogenic nanomaterial and the energy demand of pretreated wastewater. Using the data collected in task 3 (Section 3.2

3.4.1 Analysis of Energy Required to Filter Select Sizes of Nanomaterial in Wastewater

The relative energy demand was calculated using the data collected in task 3 (Section 3.2) and presented below:

3.4.1.1 Analysis using Polypropylene Membranes

The energy demand results for each treatment facility are shown in figures 51 through 54. Unfiltered samples appear to have the highest energy demand and as particle size decrease the energy demand decreases. This correlates directly with the amount of fouling or flux reduction the membrane suffered through the run. Samples pre-filtered to 2.5 nm shows almost no increase in energy demand throughout the entire run and 3.5 nm samples only show slight increases due to fouling. SMWD appears to have the highest energy consumption and IRWD seems to have the lowest energy consumption of the three plants. In figure 52, OCSD unfiltered samples is very unusual and does not follow any of the trends seen in the results so it was removed (figure 53). The membrane used for that specific run may have had imperfections.

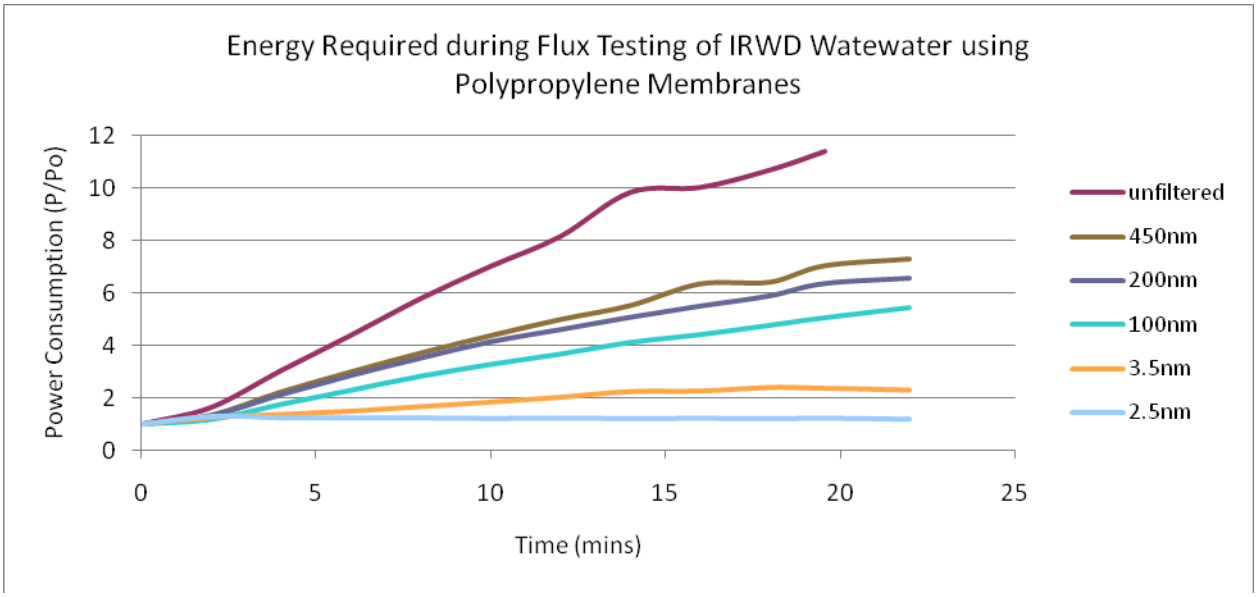

Figure 51: The Relative Energy Used During Flux Reduction Runs Using Polypropylene Membranes and Select Pre Filtered Ranges of Secondary Effluent IRWD Wastewater

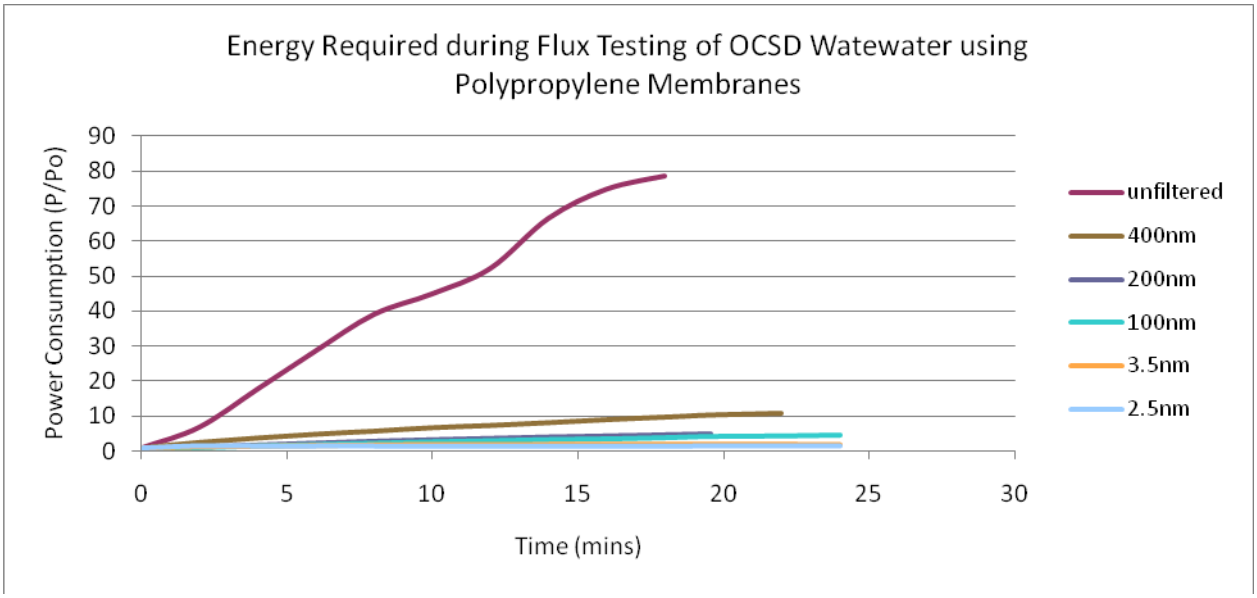

Figure 52: The Relative Energy Used During Flux Reduction Runs Using Polypropylene Membranes and Select Pre Filtered Ranges of Secondary Effluent OCSD Wastewater

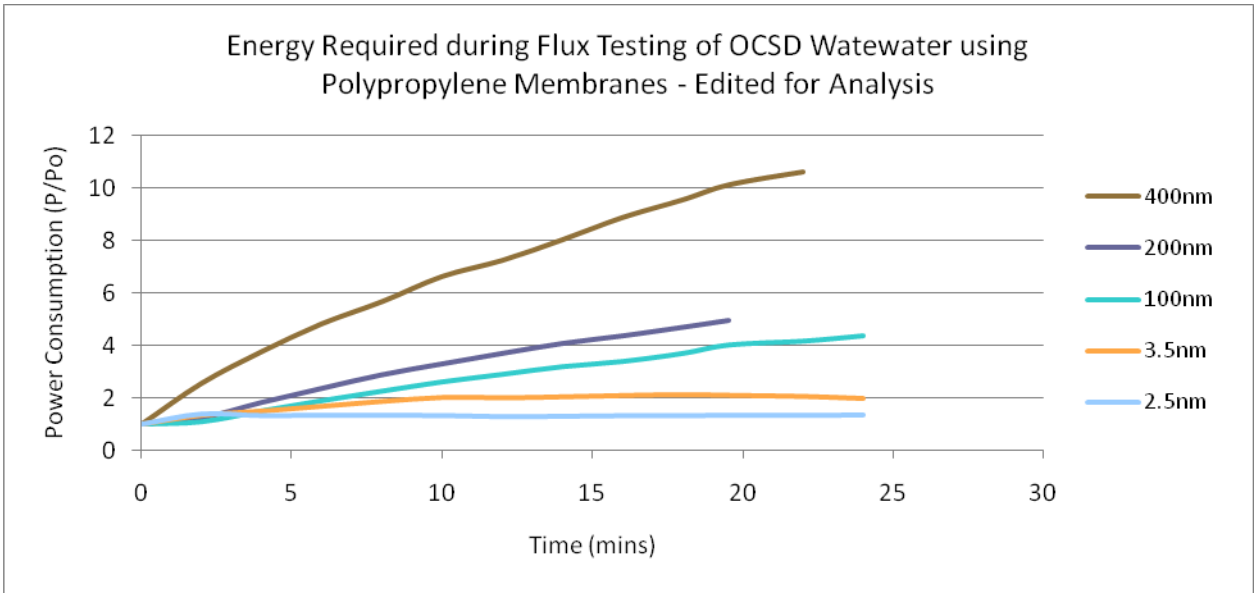

Figure 53: The Relative Energy Used During Flux Reduction Runs Using Polypropylene Membranes and Select Pre Filtered Ranges of Secondary Effluent OCSD Wastewater – Edited for Analysis

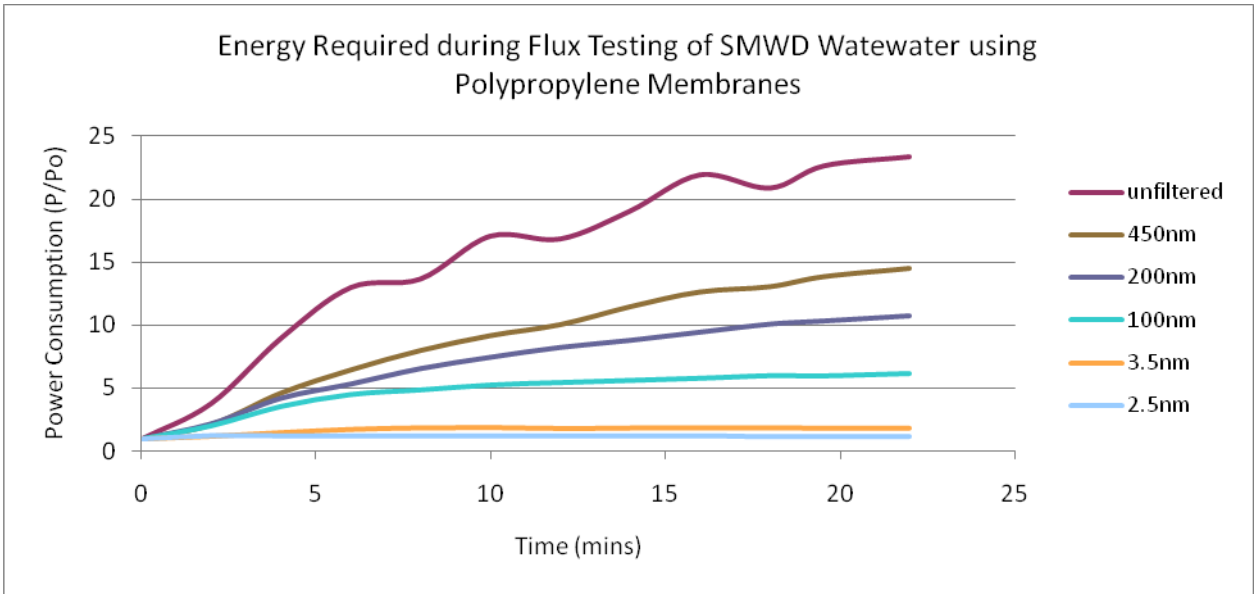

Figure 54: The Relative Energy Used During Flux Reduction Runs Using Polypropylene Membranes and Select Pre Filtered Ranges of Secondary Effluent SMWD Wastewater

3.4.1.2 Analysis using PVDF Membranes

The energy demand results using PVDF membranes for each treatment facility are shown in figures 55 through 58. The results for PVDF membranes generally appear to be the same seen with polypropylene membranes except differences in the amount of power consumed is much smaller. Due to the smaller pore size of PVDF membranes the amount of energy required to filter samples with particles smaller than 450 nm are not significantly different.

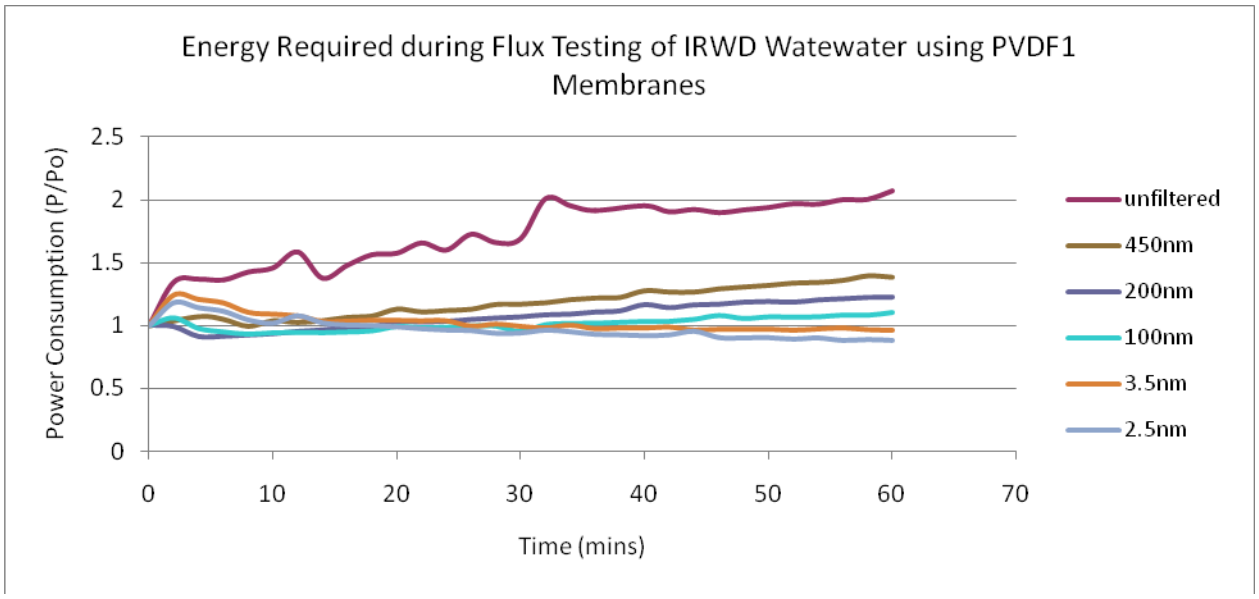

Figure 55: The Relative Energy Used During Flux Reduction Runs Using PVDF1 Membranes and Select Pre Filtered Ranges of Secondary Effluent IRWD Wastewater

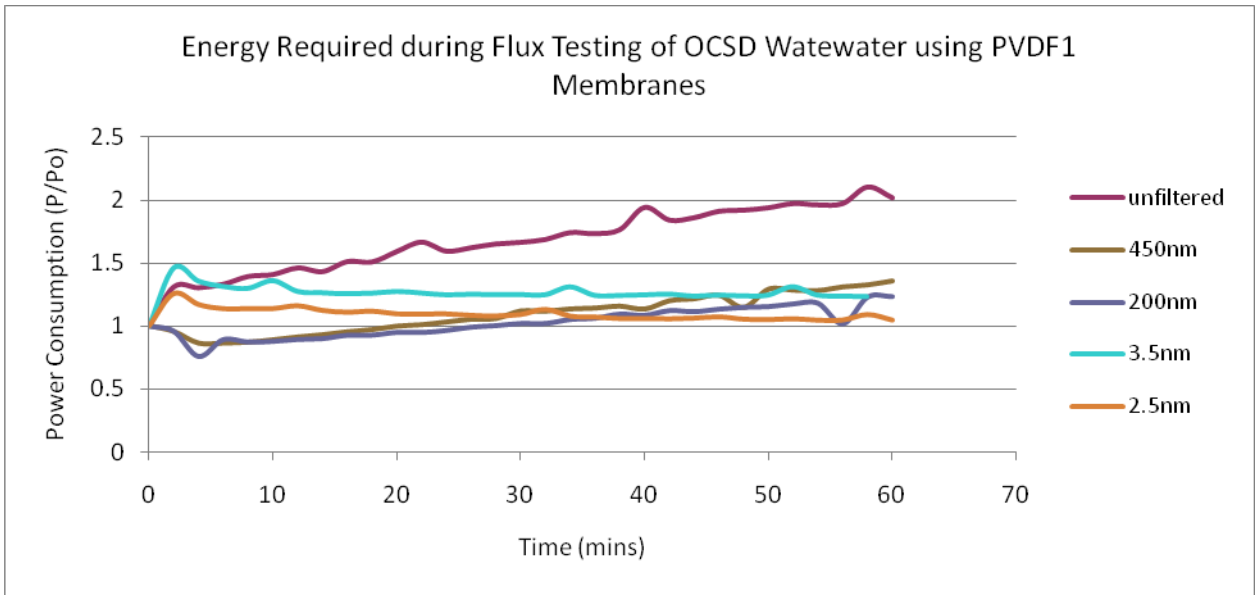

Figure 56: The Relative Energy Used During Flux Reduction Runs Using PVDF1 Membranes and Select Pre Filtered Ranges of Secondary Effluent OCSD Wastewater

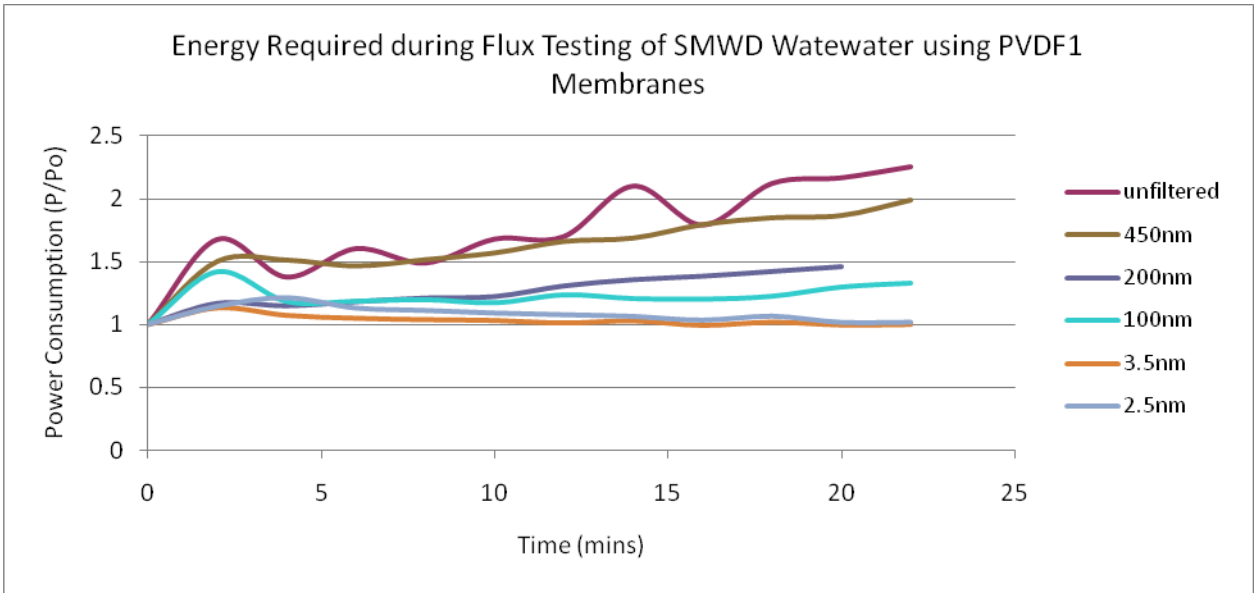

Figure 57: The Relative Energy Used During Flux Reduction Runs Using PVDF1 Membranes and Select Pre Filtered Ranges of Secondary Effluent SMWD Wastewater

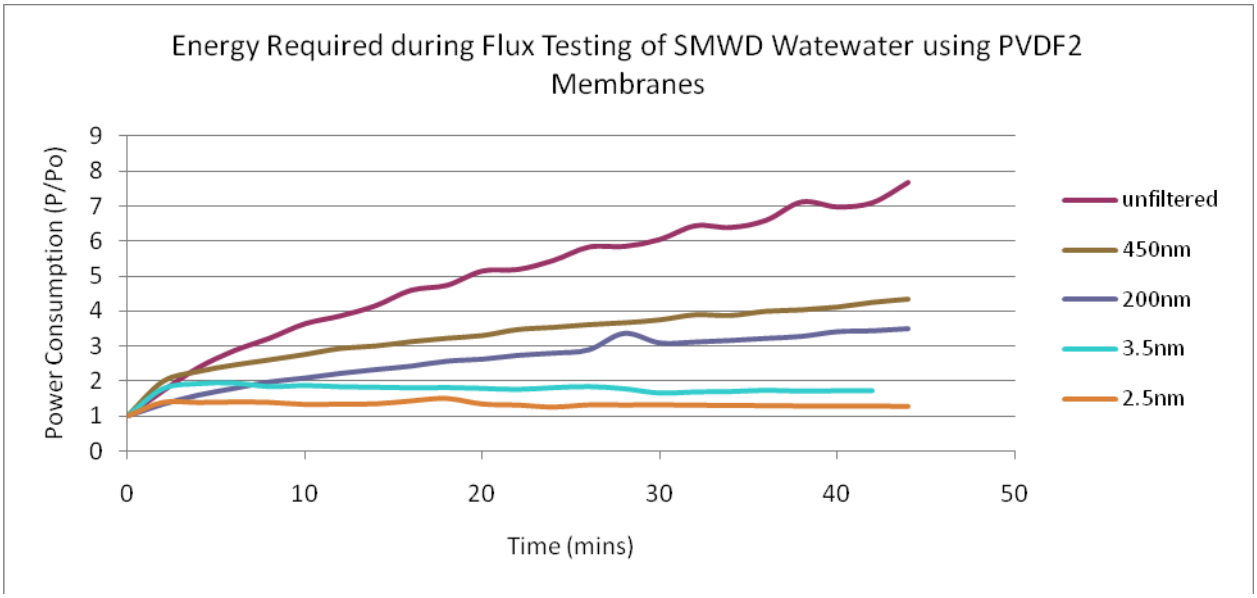

Figure 58: The Relative Energy Used During Flux Reduction Runs Using PVDF2 Membranes and Select Pre Filtered Ranges of Secondary Effluent SMWD Wastewater

3.4.2 Analysis of Energy Required to Filter Pre-Treated SMWD Wastewater

The relative energy demand was calculated using the data collected in task 3 (Section 3.3) and shown in figures 59 through 61. Overall, as the concentration of the coagulant increased the energy consumption significantly decreased. While, there are no significant differences between each coagulant use in this experiment it was found that a concentration of only 10 mg/L showed a reduction in power consumption of 20 - 30 percent. A relatively small amount of coagulant can significantly reduce membrane fouling and become more energy efficient.

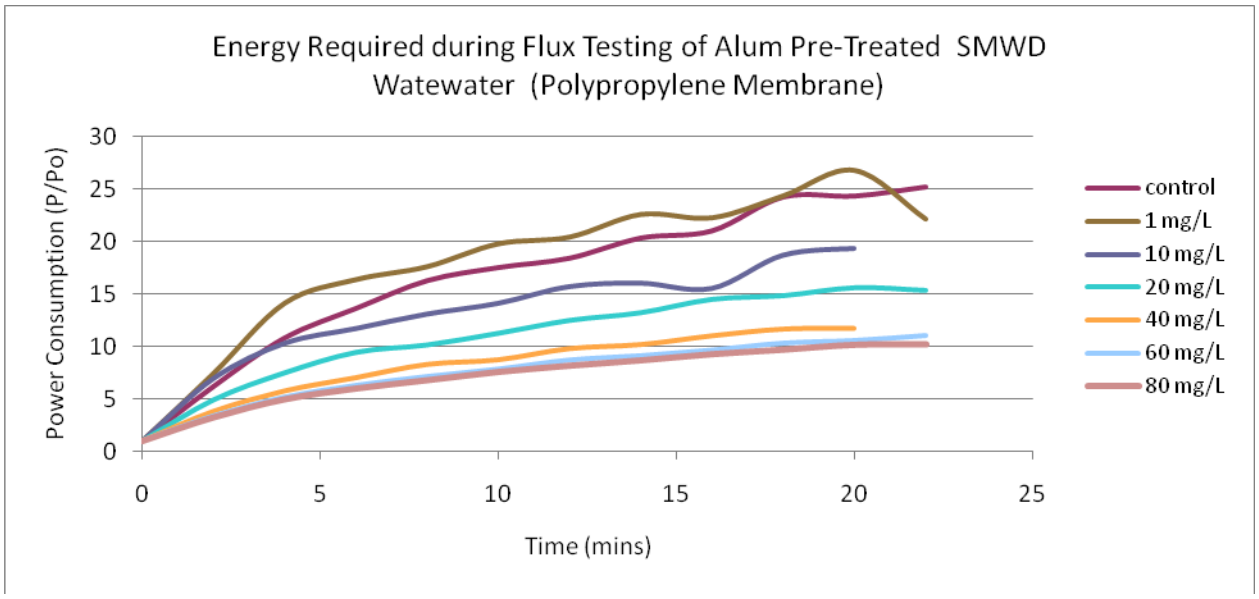

Figure 59: The Relative Energy Used During Flux Reduction Runs Using Polypropylene Membranes and Secondary Effluent SMWD Wastewater Pre-Treated With Select Alum Coagulant Concentrations

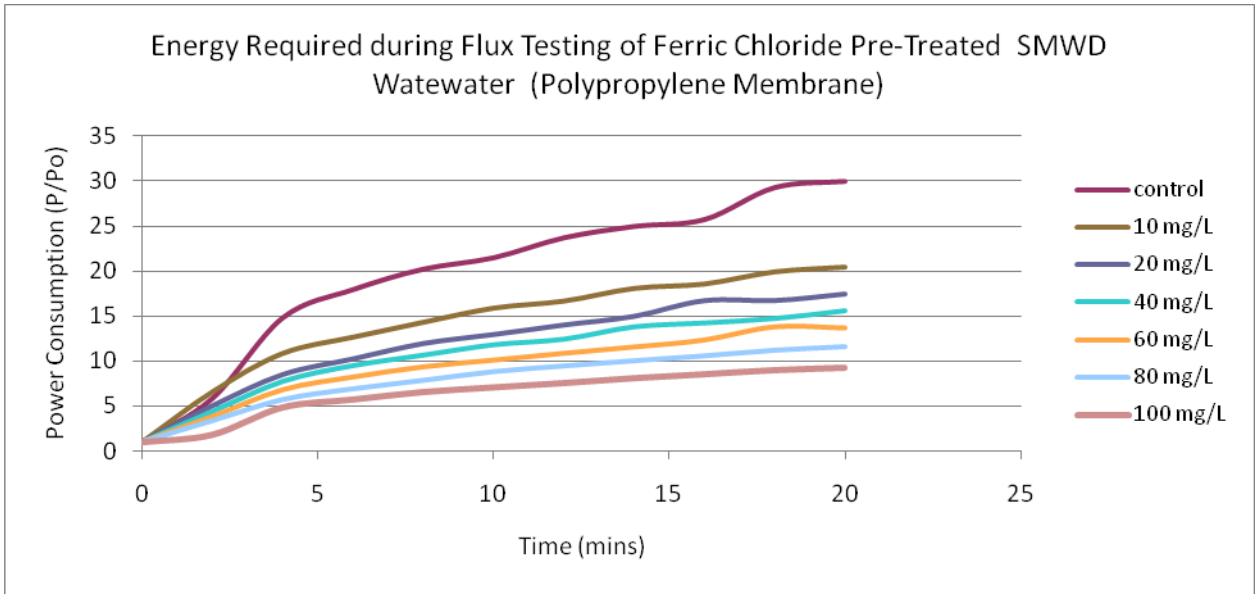

Figure 60: The Relative Energy Used During Flux Reduction Runs Using Polypropylene Membranes and Secondary Effluent SMWD Wastewater Pre-Treated With Select Ferric Chloride Coagulant Concentrations

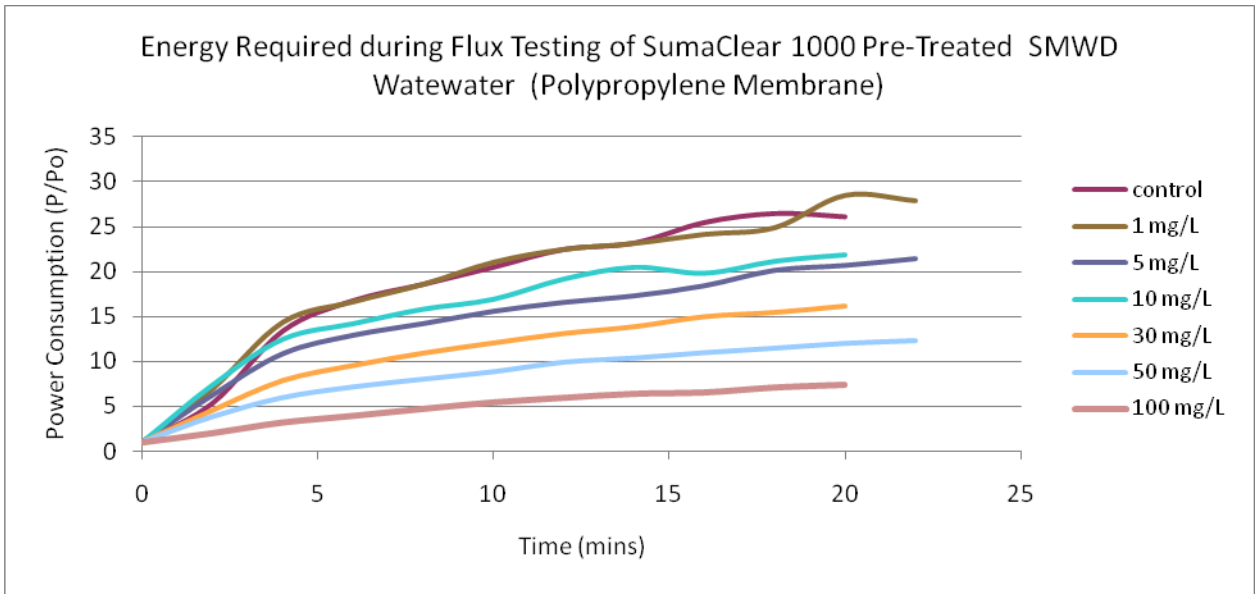

Figure 61: The Relative Energy Used During Flux Reduction Runs Using Polypropylene Membranes and Secondary Effluent SMWD Wastewater Pre-Treated With Select Polymer Coagulant Concentrations

CHAPTER 4: Conclusions

4.1 Conclusions

Results show that as wastewater samples are filtered with increasingly smaller pore sized filters the count rate in the filtrate samples are reduced, showing that not only the larger particles were removed, but the overall number of particles is decreased by the filtration process. While differences in the amount of nanoparticles between treatment plants were small, results showed that trickling filters tend to produce more nanoparticles compared to activated sludge processes. In addition, high MCRT plants were found to more effectively remove nanoscale particles. Flux analysis of MF membranes (200 nm pore size) showed that particles between 100 and 2.5 nm contributed the most to the membrane fouling. This also indicates that a significant portion of the fouling is due to nanoparticles clogging of the pores within the membrane rather than fouling due to cake formation. Fouling of UF membranes were shown to be primarily caused by cake formation rather than pore plugging. With pre-treatment of secondary effluent wastewater approximately 60 – 80 percent of nanomaterial was removed at the highest concentration tested (100 mg/L). At the same dose, the flux is shown to double with respect to an untreated sample. Furthermore, analysis of samples spiked with only 10 mg/L coagulant concentration showed a 20 to 30 percent reduction in energy consumption. The results presented in this report show that energy consumption in membrane filtration processes can be significantly reduce through the removal of nanomaterial.

4.2 Benefits to California

A survey of RO facilities in Southern California service area indicated that there are 16 reclamation facilities, 8 desalination facilities, 26 brackish water facilities, 5 municipal water treatment facilities serving more than 500 people, and 18 small municipal water treatment facilities serving less than 500 people (13). The design flow rates for 54 out of the 74 facilities were obtained. The total flow rate for the facilities with known flow rates is about 315 MGD. The overall treatment capacity of these facilities varied from 0.1 to 90 MGD. For the remaining facilities, assuming an average flow rate of 2 MGD for the larger systems and 0.25 MGD for the smaller systems, the total water treated by membrane processes in the project area is about 330 MGD.

Furthermore, a survey by American Membrane Technologies Association indicates that there are at least 345 microfiltration treatment plants (88 MGD capacity), 2 nanofiltration facilities (9 MGD), 31RO facilities (93 MGD) and six UF facilities (42 MGD) in California (14). This list is not a complete list as it does not include some major filtration facilities including the 70 MGD OCWD MF facility. Industrial membrane treatment facilities are also not included in this compilation.

There is potential to improve the energy efficiency of these membrane treatment facilities in California, as well as other industrial/municipal membrane treatment facilities outside California.

GLOSSARY

Alum	Aluminum sulfate
ASP	activated sludge process
DI	De-ionized water
Energy Commission	California Energy Commission
FSTW	Filtered secondary treated water
hr	Hour
IRWD	Irvine Ranch Water District
kcps	Kilo-counts per second
kWh	kilowatt-hour
L	Liter
M	meter
MCRT	mean cell residence time
MF	Microfiltration
mg	milligrams
MGD	million gallons per day
ml	milliliter
MWCO	Molecular weight cut off
NF	Nanofilration
nm	Nanometer
OCSD	Orange County Sanitation District
PIER	Public Interest Energy Research
PVDF	Polyvinylidene fluoride
RD&D	research, development, and demonstration
RO	Reverse Osmosis
sCOD	Soluble chemical oxygen demand
SMWD	Santa Margarita Water District
STW	Secondary Treated Water

UCI	University of California, Irvine
UF	Ultrafiltration
WWTP	Wastewater Treatment Plant

REFERENCES

1. Ganesh, R. et al. 2008. Nanoparticles as compounds of emerging concerns in wastewaters. Water Environment Federation (WEF) Technical Practice Update. http://www.wef.org/ScienceTechnologyResources/TPUs/

2. Safarik, J. and Phipps, D.W. 2006. Proceedings of the National American Membrane Society Conference. Chicago, IL. May 12-17.

3. Knudson, M.I. 1993. Bentonite In Paper: The Rest of the Story. Papermakers Conference. TAPPI Proceedings.

4. Wiesner, Mark, R. and Chellam, Shankararaman. (1992). *J. AWWA*. January, pp. 88-95.

5. Cho, J., et al. (2006). *Desalination*. 188: pp 213-216.

6. Safarik, J. and Phipps, D.W. 2006. Proceedings of the National American Membrane Society Conference. Chicago, IL. May 12-17.

7. Roorda, J.H. et al. 2004. *Water Sci. Technol*. 50: pp 87-94.

8. Aim, R. B.; Vigneswara, S.; Prasanthi, H.; Jagatheesan, H. (1997) Influence of Particle Size and Size Distribution in Granular Bed Filtration and Dynamic Microfiltration. *Water Sci. Technol.*, **36** (4), 207–215.

9. Cho, J.; Kim, S. I.; Moon, J.; Kwon, B. (2006) Determining Brownian and Shear-Induced Diffusivity of Nano- and Micro-Particles for Sustainable Membrane Filtration. *Desalination*, **188**, 213–216.

10. Kim, S.; Marion, M.; Jeong, B.; Hoek, E. M. V. (2006) Crossflow Membrane Filtration of Interacting Nanoparticle Suspensions. *J. Membr. Sci.*, **284**, 361–372.

11. Sanchis, M. I. A.; Saez, J.; Llorens, M.; Soler, A.; Ortuno, J. F. (2003) Particle Size Distribution in Slaughterhouse Wastewater Before and After Coagulation-Flocculation. *Environ. Prog.*, **22** (3), 183–188.

12. Westerhoff, Paul, et al., (2005). 2005 Progress Report. EPA STAR Grant R831713. http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/7387/report/0

13. Kennedy/ Jenks Consultants. 2005. Conceptual Evaluation of Combined UHLA and Pellet Softening Process for Reverse Osmosis Brine Stream Treatment. Report Submitted to Southern California Edison under the Statewide Emerging Technologies Program.

14. American Membrane Technology Association. 2008. www.amtaorg.com

15. Ganesh, R. et al. 2007. Proceedings of the CWEA Annual Conference, Ontario, CA. April.

16. Huang, C. et al. 2004. *Water Sci. Technol*. 50(12): pp 133-138.

17. Phenart, T. et al. 2007. Environ. Sci. Technol. 41:pp 284-290.

18. Ganesh, R., Smeraldi, J., Cooper, W.J., Leong, L.Y.C.L. 2009. Evaluation of Ensemble Techniques to Monitor Nanoparticles in Wastewater. International Conference on the Environmental Implications and Applications of Nanotechnology. Amherst, MA. June.

APPENDIX A:
Common Editor / Proofreading Marks

Symbol	Example	Meaning
	weeke	delete letter, word, phrase
	febuary	insert
	power plant	insert space
	close up	close up
	1st	spell out
	fulltime	insert hyphen
	B	make letter lowercase
	B	make letter lowercase
	b	make letter uppercase
	sotry	transpose letters, words
	Ph. D.	insert period
	members who	insert comma
	end. In the	start new paragraph
STET	final report	let it stand (ignore mark)
ital	Time Magazine	change to italic
B or bold	Figure 12	change to bold

APPENDIX B:
Data Sets

Table 1. Task 1 data set for IRWD primary influent, primary effluent, and secondary effluent samples relating COD and count rate to filtration size (particle size)

Plant	Sample	Filter size	COD	Count Rate
IRWD	Primary Influent	0.45	109	196.2
IRWD	Primary Influent	0.2	110	67.9
IRWD	Primary Influent	0.1	104	66.1
IRWD	Primary Influent	0.08	103	60.2
IRWD	Primary Influent	0.05	115	54.0
IRWD	Primary Influent	0.03	108	31.1
IRWD	Primary Influent	0.01	165	19.1
IRWD	Primary Effluent	0.45	97	397.6
IRWD	Primary Effluent	0.2	93	97.6
IRWD	Primary Effluent	0.1	93	109.8
IRWD	Primary Effluent	0.08	94	41.8
IRWD	Primary Effluent	0.05	95	64.4
IRWD	Primary Effluent	0.03	100	24.9
IRWD	Primary Effluent	0.01	94	51.0
IRWD	Secondary Effluent	0.45	21	57.6
IRWD	Secondary Effluent	0.2	20	50.1
IRWD	Secondary	0.1	22	49.2

	Effluent			
	Secondary			
IRWD	Effluent	0.08	21	56.7
	Secondary			
IRWD	Effluent	0.05	22	19.0
	Secondary			
IRWD	Effluent	0.03	25	20.2
	Secondary			
IRWD	Effluent	0.01	29	47.2

Table 2. Task 1 data set for SMWD primary influent, primary effluent, and secondary effluent samples relating COD and count rate to filtration size (particle size)

Plant	Sample	Filter size	COD	Count Rate
	Primary			
SMWD	Influent	0.45	112	793.5
	Primary			
SMWD	Influent	0.2	94	85.3
	Primary			
SMWD	Influent	0.2	93	102.9
	Primary			
SMWD	Influent	0.1	84	89.5
	Primary			
SMWD	Influent	0.08	89	126.25
	Primary			
SMWD	Influent	0.05	85	25
	Primary			
SMWD	Influent	0.05	84	
	Primary			
SMWD	Influent	0.03	98	26.75
	Primary			
SMWD	Influent	0.03	97	25.2
	Primary			
SMWD	Influent	0.01	7	462.6
	Primary			
SMWD	Effluent	0.45	139	1275.1
	Primary			
SMWD	Effluent	0.45	143	1547.7
	Primary			
SMWD	Effluent	0.2	114	152.4

SMWD	Primary Effluent	0.1	110	126.3
SMWD	Primary Effluent	0.08	107	93.4
SMWD	Primary Effluent	0.08	108	112.05
SMWD	Primary Effluent	0.05	112	25
SMWD	Primary Effluent	0.05	99	24.5
SMWD	Primary Effluent	0.03	114	30.7
SMWD	Primary Effluent	0.01	151	66.45
SMWD	Secondary Effluent	0.45	43	359.55
SMWD	Secondary Effluent	0.2	36	312.5
SMWD	Secondary Effluent	0.2	36	114
SMWD	Secondary Effluent	0.1	24	60.05
SMWD	Secondary Effluent	0.08	36	54.95
SMWD	Secondary Effluent	0.08	37	57.25
SMWD	Secondary Effluent	0.05	36	55.6
SMWD	Secondary Effluent	0.03	42	65.4
SMWD	Secondary Effluent	0.01	49	53.65

Table 3. Task 1 data set for OCSD primary influent, primary effluent, and secondary effluent samples relating COD and count rate to filtration size (particle size)

Plant	Sample	Filter size	COD	Count Rate
OCSD	Primary Influent	0.45	1665	613.6
OCSD	Primary Influent	0.2	165	108.2
OCSD	Primary Influent	0.1	160	91.95
OCSD	Primary Influent	0.1	163	90.15

OCSD	Primary Influent	0.08	154	67.55
OCSD	Primary Influent	0.08	149	76.4
OCSD	Primary Influent	0.05	157	55.85
OCSD	Primary Influent	0.05	139	55.85
OCSD	Primary Influent	0.03	158	40.75
OCSD	Primary Influent	0.01	165	1095.733
OCSD	Primary Effluent	0.45	165	472.3
OCSD	Primary Effluent	0.2	165	131.25
OCSD	Primary Effluent	0.2	164	134.9
OCSD	Primary Effluent	0.1	160	92.5
OCSD	Primary Effluent	0.08	156	93.7
OCSD	Primary Effluent	0.08	157	72.9
OCSD	Primary Effluent	0.05	163	37.45
OCSD	Primary Effluent	0.03	165	35.05
OCSD	Primary Effluent	0.01	165	31.3
OCSD	Secondary Effluent	0.45	29	148.55
OCSD	Secondary Effluent	0.45	26	192
OCSD	Secondary Effluent	0.2	30	93.35
OCSD	Secondary Effluent	0.1	24	68.85
OCSD	Secondary Effluent	0.1	23	73.05
OCSD	Secondary Effluent	0.08	29	53.5
OCSD	Secondary Effluent	0.05	24	70.6
OCSD	Secondary Effluent	0.05	28	51
OCSD	Secondary Effluent	0.03	25	35.1
OCSD	Secondary Effluent	0.01	29	28.7

Table 4. Flux results for polypropylene membranes using OCSD secondary effluent

flux

	(L/m2/hr)						
time (s)	DI water	2.5nm	3.5nm	100nm	200nm	450nm	unfiltered
0.00	398.13	398.13	398.13	398.13	398.13	398.13	398.13
1.99	397.90	290.71	297.51	363.78	320.95	155.83	57.20
3.99	390.84	303.12	266.42	264.46	217.42	105.74	22.34
5.99	405.24	300.02	237.44	209.78	168.00	82.50	13.86
7.99	406.10	300.57	214.09	176.15	137.74	70.27	10.17
9.99	404.17	302.99	198.22	152.34	120.33	60.08	8.85
11.99	400.07	312.54	199.38	137.16	107.37	54.98	7.62
13.99	397.14	309.08	195.97	124.61	97.35	49.60	5.98
15.99	403.21	304.11	191.28	117.29	90.92	44.87	5.32
17.99	395.89	303.66	188.55	107.58	84.54	41.70	5.07
19.54	391.50	301.01	190.52	98.93	80.05	39.32	
21.99	387.36	301.91	194.53	95.50		37.52	
23.99		297.60	202.02	91.05			

Table 5. Flux results for polypropylene membranes using IRWD secondary effluent

	flux (L/m2/hr)						
time (s)	DI water	2.5nm	3.5nm	100nm	200nm	450nm	unfiltered
0.00	398.13	398.13	398.13	398.13	398.13	398.13	398.13
1.99	397.90	290.32	297.77	317.74	283.16	278.44	228.03
3.99	390.84	303.86	272.79	213.49	176.40	167.87	122.69
5.99	405.24	305.58	249.92	163.54	131.35	124.87	85.12
7.99	406.10	305.01	224.11	132.60	106.61	100.56	64.49
9.99	404.17	309.86	203.30	114.41	90.65	85.43	53.21
11.99	400.07	306.90	184.39	102.17	81.51	74.86	45.77
13.99	397.14	309.94	166.75	91.20	73.97	67.65	37.96
15.99	403.21	307.90	165.12	85.02	68.24	58.84	37.26
17.99	395.89	311.24	155.89	78.68	63.72	58.24	34.93
19.54	391.50	307.12	157.74	74.23	59.03	53.08	32.77
21.99	387.36	316.90	162.73	68.95	57.19	51.18	

Table 6. Flux results for polypropylene membranes using SMWD secondary effluent

	flux ($L/m^2/hr$)						
time (mins)	DI water	2.5nm	3.5nm	100nm	200nm	450nm	unfiltered
0	398.13	398.13	398.13	398.13	398.13	398.13	398.13
1.99	397.90	351.29	348.20	207.06	191.72	197.23	110.90
3.99	390.84	354.51	280.51	118.61	99.79	91.09	47.01
5.99	405.24	354.16	240.50	93.78	78.85	65.20	32.44

7.99	406.10	356.27	224.99	86.73	64.11	52.66	30.83
9.99	404.17	355.09	221.87	80.32	56.45	45.93	24.70
11.99	400.07	358.40	230.76	77.52	51.12	41.95	25.03
13.99	397.14	355.99	226.81	75.21	47.86	36.78	22.12
15.99	403.21	352.81	224.92	73.02	44.60	33.37	19.24
17.99	395.89	370.17	224.72	70.55	41.78	32.31	20.20
19.54	391.50	367.51	227.74	70.65	40.76	30.44	18.63
21.99	387.36	365.54	228.14	68.60	39.23	29.08	18.05
23.99					40.06	27.61	
25.99					37.17	26.79	
27.99					36.26	25.30	
29.99					35.40	24.59	
31.99					34.88	23.38	
33.99					34.25	23.74	
35.99					33.46	22.87	

Table 7. Percent Flux results for PVDF1 membranes using OCSD secondary effluent

	flux					
time (mins)	unfiltered (DI)	unfiltered	450nm (DI)	450nm	200nm (DI)	200nm
0	100%=		100%=		100%=	
1.9857143	0.008843339	83.3127	0.00884	86.9741	0.00844	98.3173
3.9857143		83.7754		96.3845		123.942
5.9857143		82.0195		96.3094		105.477
7.9857143		78.3763		95.5206		107.918
9.9857143		77.5406		93.464		107.17
11.985714		74.733		91.1727		105.319
13.985714		76.2636		89.4167		104.61
15.985714		72.226		87.2193		101.628
17.985714		72.3481		85.6605		101.49
19.985714		68.564		83.341		99.1673
21.985714		65.4841		82.3456		99.315
23.985714		68.4513		80.6272		97.6712
25.985714		67.287		78.9744		95.0727
27.985714		66.0663		78.5425		93.9408
29.985714		65.5686		74.3543		92.4249
31.985714		64.6578		74.4857		92.4249
33.985714		62.6203		73.2462		89.6099
35.985714		62.9583		72.8612		88.8224
37.985714		61.8034		71.894		86.1747
39.985714		56.1628		73.3401		86.9228
41.985714		59.2493		69.2928		84.0782
43.985714		58.6202		68.4007		84.7081

45.985714	57.0615	66.917	83.212
47.985714	56.808	72.5231	82.1489
49.985714	56.2258	64.3721	81.7848
51.985714	55.2775	64.7572	80.2985
53.985714	55.5873	64.898	79.9638
55.985714	55.2681	63.4613	92.6907
57.985714	51.8127	62.7006	76.7649
59.985714	54.038	61.2639	76.568
61.985714	52.8925	60.6347	
63.985714	52.977	59.5078	

Table 8. Percent Flux results for PVDF1 membranes using IRWD secondary effluent

	flux							
time (mins)	unfiltered (DI)	unfiltered	450nm (DI)	450nm	200nm (DI)	200nm	100nm (DI)	100nm
0	100%=		100%=		100%=		100%=	
1.985714	0.00966459		0.00733	63.509	0.00796	101.20		94.465
3	8	74.4267	5	2	3	3	0.00705	8
3.985714				93.137		110.03		102.55
3		73.1854		3		9		7
5.985714				94.993		109.77		105.48
3		73.5376		9		8		8
7.985714				100.32		108.54		107.46
3		70.2727		6		8		6
9.985714				96.046				106.27
3		68.7262		8		107.38		7
11.98571				97.326		105.27		105.80
4		63.1845		1		4		6
13.98571				95.967		103.92		106.17
4		72.7902		5		9		1
15.98571				93.612		101.97		105.57
4		67.7381		8		9		1
17.98571				92.673		101.23		104.60
4		64.078		2		8		5
19.98571				88.190		97.536		100.87
4		63.6055		1		6		4
21.98571				89.922		97.484		101.89
4		60.4608		2		5		8
23.98571		62.6002		89.061		97.098		101.56

4		8	7	8
25.98571		88.246	95.649	
4	58.0465	7	3	100.52
27.98571		85.359	94.627	100.63
4	60.3663	8	4	8
29.98571		85.201	93.834	105.19
4	59.2494	3	9	4
31.98571		84.374	92.354	
4	49.8585	9	3	99.508
33.98571		82.642	91.947	98.507
4	51.2848	8	6	4
35.98571		81.759	90.539	98.448
4	52.3072	8	9	6
37.98571		81.465	89.768	97.648
4	83.0316	4	3	1
39.98571		78.046	85.910	97.059
4	51.3019	5	2	5
41.98571		78.703		96.988
4	52.6165	1	87.735	9
43.98571		78.703	86.066	95.470
4	52.0838	1	6	3
45.98571		77.152	85.691	
4	52.7797	2	3	92.798
47.98571		76.269	84.492	94.858
4	52.1697	1	1	1
49.98571		75.533	84.137	93.716
4	51.6714	3	6	3
51.98571		74.503	84.523	93.928
4	50.8981	1	4	2
53.98571		74.197	83.230	93.692
4	50.9669	4	4	7
55.98571		73.314	82.583	92.480
4	50.0475	4	9	2
57.98571		71.435	81.885	92.586
4	49.996	1	3	2
59.98571		71.978	81.718	90.773
4	48.3635	5	5	3
61.98571		71.729	79.132	91.232
4	48.9134	4	5	4
63.98571				
4				

Table 9. Percent Flux results for PVDF1 membranes using SMWD secondary effluent

	flux							
time (mins)	unfiltered (DI)	unfiltered	450nm (DI)	450nm	200nm (DI)	200nm	100nm (DI)	100nm
0								
0.4857143	100%=	50.920325	100%=	52.5356	100%=	84.3091	100%=	54.6002
0.9857143	0.007368	68.925879	0.00872	40.9215	0.00764	79.7568	0.0083	72.9331
1.4857143		66.537595		76.4695		88.0209		73.5273
1.9857143		77.905828		95.8969		89.6995		82.1636
2.4857143		77.046045		70.7578		87.2892		81.292
2.9857143		87.411198		57.0045		86.6866		95.5934
3.4857143		93.955097		62.9417		85.3523		79.6282
3.9857143		63.623889		73.1251		87.4613		82.4013
4.4857143		74.275636		67.7516		85.4383		91.7903
4.9857143		64.579202		69.2923		84.5775		79.4697
5.4857143		70.454381		69.7432		84.3193		84.8971
5.9857143		68.161629		65.497		82.8128		81.9655
6.4857143		58.866646		57.375		73.6184		81.7304
6.9857143		80.915066		64.1442		82.8128		85.8083
7.4857143		67.9228		66.9249		80.7898		80.8563
7.9857143		75.565309		64.1442		82.1241		83.9067
8.4857143		81.058363		64.783		83.2862		83.7086
8.9857143		49.103121		63.2799		80.2303		82.9955
9.4857143		56.411271		63.2423		85.9979		85.4517
9.9857143		76.99828		62.6035		75.9261		90.7206
10.485714		80.819534		61.852		78.4655		82.5994
10.985714		48.864293		59.5974		75.4526		81.8467
11.485714		72.12618		60.8374		75.5817		81.8467
11.985714		59.659337		58.4325		75.84		77.9247
12.485714		57.605413		59.8604		75.4526		87.2344
12.985714		58.321898		60.0107		73.2575		78.4793
13.485714		51.013749		58.6579		73.6879		88.2645
13.985714		44.80421		58.2446		72.0953		78.7962
14.485714		50.77492		57.23		71.2345		81.2128
14.985714		58.512961		57.7937		73.1714		97.7723
15.485714		80.055283		56.5912		73.0853		77.6474
15.985714		58.465195		50.5037		70.2445		77.6077
16.485714		53.640861		55.276		70.8902		76.1023
16.985714		51.682468		52.0068		70.2015		77.3304
17.485714		52.351188		54.4493		69.9002		92.1072
17.985714		51.873531		54.1111		69.8141		82.5597
18.485714		52.972142		53.2468		68.3507		78.3208

18.985714	49.580778	53.8856	67.9203	77.0135
19.485714	51.061514	53.7729	69.3837	79.7866
19.985714	51.778	52.7959	67.662	73.9631
20.485714	47.765682	52.0444	116.299	76.3796
20.985714	48.864293	54.1111	9.81357	77.1324
21.485714	50.822686	44.8671		74.5573
21.985714		49.677		74.3196

Table 10. Particle analysis of IRWD feed samples used in polypropylene flux analysis

Feed Sample	Count Rate	Z-Avg	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD unfiltered feed 1	153.7	1391	94.68	94.42	93.6
IRWD unfiltered feed 2	149.2	715.1	132.6	131.2	126.9
IRWD unfiltered feed 3	147.1	447.1	212.3	115.2	50.51
Average	**150.0**	**851.1**	**146.5**	**113.6**	**90.3**
IRWD 0.45 feed 1	62	141.5	118.8	104.2	84.47
IRWD 0.45 feed 2	65	138.4	121.7	109.2	90.69
IRWD 0.45 feed 3	63.2	130	143	124.9	89.13
Average	**63.4**	**136.6**	**127.8**	**112.8**	**88.1**
IRWD 0.2 feed 1	56.2	167.2	117.2	109.6	97.98
IRWD 0.2 feed 2	50.1	143.9	112.5	93.97	72.78
IRWD 0.2 feed 3	48.4	146.4	102	86.78	70.63
Average	**51.6**	**152.5**	**110.6**	**96.8**	**80.5**
IRWD 0.1 Feed 1	38.6	973.7	56.55	55.93	54.92
IRWD 0.1 Feed 2	40.6	201.8	143.5	76.56	38.4
IRWD 0.1 Feed 3	40.9	238.4	132.4	58.53	34.64
Average	**40.0**	**471.3**	**110.8**	**63.7**	**42.7**

Table 11. Particle analysis of IRWD permeate samples used in polypropylene flux analysis

Permeate Sample	Count Rate	Z-Avg	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)

IRWD unfilt PP-mem 1	19.2	438.1	135.3	65.42	38.16
Average	**19.2**	**438.1**	**135.3**	**65.4**	**38.2**
IRWD 0.45 PP membrane 1	31.9	459.3	108.3	105.4	100.9
IRWD 0.45 PP membrane 2	50.9	391.6	210.6	585.3	92.59
IRWD 0.45 PP membrane 3	55.8	405.7	155.7	205.7	76.29
Average	**46.2**	**418.9**	**158.2**	**298.8**	**89.9**
IRWD 0.2 PP membrane 1	18.2	158.1	117.8	39.1	22.66
IRWD 0.2 PP membrane 2	15.2	91.85	432.2	1.186	1.103
IRWD 0.2 PP membrane 3	17.7	127	396.5	126.9	21.89
Average	**17.0**	**125.7**	**315.5**	**55.7**	**15.2**
IRWD 0.1 PP-mem 1	21.6	166	478.3	714.2	74.92
IRWD 0.1 PP-mem 2	27	192.6	584.5	755.9	63.87
IRWD 0.1 PP-mem 3	22	164.9	681.4	1007	77.16
Average	**23.5**	**174.5**	**581.4**	**825.7**	**72.0**

Table 12. Particle analysis of OCSD feed samples used in polypropylene flux analysis

Feed Sample	Count Rate	Z-Avg	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD unfilt feed 1	121.40	129.80	114.20	81.40	52.67
OCSD unfilt feed 2	120.00	119.20	114.20	72.05	31.04
OCSD unfilt feed 3	112.80	110.70	341.40	329.20	53.59
Average	**118.07**	**119.90**	**189.93**	**160.88**	**45.77**
OCSD 0.45 filt feed 1	112.30	324.50	74.06	71.17	67.76

OCSD 0.45 filt feed 2	110.80	231.30	90.11	82.56	74.06
OCSD 0.45 filt feed 3	106.40	134.90	114.70	74.16	51.80
Average	**109.83**	**230.23**	**92.96**	**75.96**	**64.54**
OCSD 0.2 feed 1	71.20	281.60	72.59	68.53	63.85
OCSD 0.2 feed 2	73.70	333.30	66.88	63.56	59.90
OCSD 0.2 feed 3	78.00	208.00	102.10	61.32	41.65
Average	**74.30**	**274.30**	**80.52**	**64.47**	**55.13**
OCSD 0.1 feed 1	49.10	383.50	93.88	53.05	38.09
OCSD 0.1 feed 2	49.90	460.80	84.88	79.23	72.73
OCSD 0.1 feed 3	47.30	278.70	111.10	58.98	42.90
Average	**48.77**	**374.33**	**96.62**	**63.75**	**51.24**

Table 13. Particle analysis of OCSD permeate samples used in polypropylene flux analysis

Permeate Sample	Count Rate	Z-Avg	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD unfilt PP membrane 1	61.20	220.90	106.80	97.58	86.05
OCSD unfilt PP membrane 2	58.80	147.80	210.60	191.80	35.46
OCSD unfilt PP membrane 3	56.30	133.60	281.40	232.90	30.79
Average	**58.77**	**167.43**	**199.60**	**174.09**	**50.77**
OCSD 0.45 PP membrane 1	22.00	207.30	768.00	611.90	44.91
OCSD 0.45 PP membrane 2	22.00	191.00	775.70	1320.00	82.52
OCSD 0.45 PP membrane 3	24.60	158.90	636.60	1186.00	89.93
Average	**22.87**	**185.73**	**726.77**	**1039.30**	**72.45**
OCSD 0.2 PP membrane 1	22.70	274.40	61.83	58.32	54.55
OCSD 0.2 PP membrane 2	28.80	509.50	54.15	52.14	49.95
OCSD 0.2 PP	26.10	336.20	67.37	63.90	60.14

membrane 3					
Average	**25.87**	**373.37**	**61.12**	**58.12**	**54.88**
OCSD 0.1 PP membrane 1	24.60	309.40	67.44	60.95	54.86
OCSD 0.1 PP membrane 2	21.00	104.40	284.20	157.50	45.59
OCSD 0.1 PP membrane 3	22.90	102.70	401.20	151.30	30.74
Average	**22.83**	**172.17**	**250.95**	**123.25**	**43.73**

Table 14. Particle analysis of SMWD feed samples used in polypropylene flux analysis

Feed Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
SMWD unfilted - feed 1	843.2	213.8	453.3	751.3	121.5
SMWD unfilted - feed 2	853.8	227.4	200.5	203.1	158.9
SMWD unfilted - feed 3	838.9	219.8	455.6	744.7	126.6
Average	845.30	220.33	369.80	566.37	135.67
SMWD 0.45 feed 1	357.5	158.9	325.6	544.5	107.8
SMWD 0.45 feed 2	354	150.4	166.5	154.4	105
SMWD 0.45 feed 3	352.9	149	190.9	81.28	28.32
Average	354.80	152.77	227.67	260.06	80.37
SMWD 0.2 feed 1	198.3	297.7	179.7	88.56	40.66
SMWD 0.2 feed 2	188.1	283.3	161.2	55.47	28.23
SMWD 0.2 feed 3	187.2	304.7	178.6	79.79	37.55
Average	191.20	295.23	173.17	74.61	35.48
SMWD 0.1 feed 1	235.1	162.6	157.6	149.3	116.5

SMWD 0.1 feed 2	232.8	154.4	145.3	134.8	107.6
SMWD 0.1 feed 3	229.2	146.5	156.7	142.9	101.2
Average	**232.367**	**154.5**	**153.2**	**142.333**	**108.433**

Table 15. Particle analysis of SMWD permeate samples used in polypropylene flux analysis

Permeate Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
SMWD unfilt pp MEM 1	15.3	97.67	477.3	147.2	36.37
SMWD unfilt pp MEM 2	22	258.2	58.48	46.52	37.96
SMWD unfilt pp MEM 3	29.2	83.62	597.6	369.6	43.22
Average	22.17	146.50	377.79	187.77	39.18
SMWD 0.45 PP MEM 1	32.3	149.7	78.04	37.62	22.2
SMWD 0.45 PP MEM 2	34.8	120.6	82.14	69.95	59.19
SMWD 0.45 PP MEM 3	35.4	166.5	76.83	69.86	63.02
Average	34.17	145.60	79.00	59.14	48.14
SMWD 200 PP MEM 1	69.4	130.2	167.1	144.6	81.59
SMWD 200 PP MEM 2	64.8	116.6	274	316.7	72.21
SMWD 200 PP MEM 3	61.7	117.8	151.1	49.42	23.67
Average	65.30	121.53	197.40	170.24	59.16
SMWD 0.1 PP mem 1	82.3	218.3	110.1	47.65	29.37
SMWD 0.1 PP mem 2	83.2	200.5	111.5	42.45	23.99
SMWD 0.1 PP mem 3	83.2	199.1	123.3	51.14	30.81

Average	**82.9**	**205.967**	**114.967**	**47.08**	**28.0567**

Table 16. Particle analysis of IRWD feed samples used in PVDF1 flux analysis

Feed					
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF unfilt feed 1	167.8	469.3	181	94.4	45.1
IRWD PVDF unfilt feed 2	170.9	732.4	142.2	57.41	32.86
IRWD PVDF unfilt feed 3	182.4	643.6	146.4	59.62	33.42
Average	**173.7**	**615.1**	**156.5333**	**70.47667**	**37.12667**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF 450 feed 1	127.7	482.9	143.2	142.3	137.7
IRWD PVDF 450 feed 2	135.3	769.4	148.2	147.2	141.3
IRWD PVDF 450 feed 3	135	459.1	162.4	162.1	153.9
Average	**132.6667**	**570.4667**	**151.2667**	**150.5333**	**144.3**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF 200 feed 1	54.9	406.8	101.4	97.8	92.49
IRWD PVDF 200 feed 2	51	193.1	156.4	115.9	67.05
IRWD PVDF 200 feed 3	49.3	205.9	125.1	63.79	34.35
Average	**51.73333**	**268.6**	**127.6333**	**92.49667**	**64.63**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF	52.5	424.6	118.6	115.6	109.7

100 feed 1 IRWD PVDF					
100 feed 2 IRWD PVDF	43.3	451.9	101.9	98.55	93.39
100 feed 3	42.5	525.8	99.74	96.65	92.06
Average	**46.1**	**467.4333**	**106.7467**	**103.6**	**98.38333**

Table 17. Particle analysis of IRWD permeate samples used in PVDF1 flux analysis

Permeate					
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF unfilt eff 1	61.9	1448	412.4	417.6	410
IRWD PVDF unfilt eff 2	63	1566	350.5	354.3	350
IRWD PVDF unfilt eff 3	61.4	1240	337.2	342.8	333.2
Average	**62.1**	**1418**	**366.7**	**371.5667**	**364.4**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF 450 eff 1	17	1508	289.7	293.3	286.2
IRWD PVDF 450 eff 2	17.3	3249	110.6	110.3	109.1
IRWD PVDF 450 eff 3	17.9	3636	352.5	356.1	352.4
Average	**17.4**	**2797.667**	**250.9333**	**253.2333**	**249.2333**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF 200 eff 1	20.6	2903	184.7	185.9	183.8
IRWD PVDF 200 eff 2	19.3	6123	0	0	0
IRWD PVDF 200 eff 3	20.8	1856	327.6	332.5	324.3
Average	**20.23333**	**3627.333**	**170.7667**	**172.8**	**169.3667**

Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
IRWD PVDF 100 eff 1	24.3	2620	141.8	142.5	142.5
IRWD PVDF 100 eff 2	22.9	2936	137.9	137.9	136.2
IRWD PVDF 100 eff 3	23.8	2963	122.4	123.1	123.1
Average	**23.66667**	**2839.667**	**134.0333**	**134.5**	**133.9333**

Table 18. Particle analysis of OCSD feed samples used in PVDF1 flux analysis

Feed Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD PVDF unfilt feed 1	196.9	251.8	132.2	70.2	46.05
OCSD PVDF unfilt feed 2	191	203.3	148.2	83.09	48.78
OCSD PVDF unfilt feed 3	202.8	288.4	134.4	69.19	43.51
Average	**196.9**	**247.8333**	**138.2667**	**74.16**	**46.11333**

Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD PVDF 450 feed 1	146	146.3	129.6	83.4	50.86
OCSD PVDF 450 feed 2	146.3	149.5	119.5	71.42	42.68
OCSD PVDF 450 feed 3	141.8	126.8	112.8	59.14	26.18
Average	**144.7**	**140.8667**	**120.6333**	**71.32**	**39.90667**

Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD PVDF 200 feed 1	88.8	210.6	132	76.92	51.35
OCSD PVDF	85.2	229.9	115.4	64.21	44.64

200 feed 2 OCSD PVDF					
200 feed 3	86.5	208.8	127.3	68.84	44.05
Average	**86.83333**	**216.4333**	**124.9**	**69.99**	**46.68**

Table 19. Particle analysis of OCSD permeate samples used in PVDF1 flux analysis

Permeate					
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD PVDF unfilt eff 1	38	2254	190.1	191.2	191.2
OCSD PVDF unfilt eff 2	35.6	2081	287.6	289.7	286.8
OCSD PVDF unfilt eff 3	35.1	2181	254.1	255.5	255.1
Average	**36.23333**	**2172**	**243.9333**	**245.4667**	**244.3667**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD PVDF 450 eff 1	33.6	1957	164.2	165.1	165.1
OCSD PVDF 450 eff 2	33.3	1741	349.3	352.5	349.8
OCSD PVDF 450 eff 3	30.8	1438	247.9	249.7	247
Average	**32.56667**	**1712**	**253.8**	**255.7667**	**253.9667**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
OCSD PVDF 200 eff 1	140.8	1541	164.2	165.1	165.1
OCSD PVDF 200 eff 2	136.3	1113	189.8	190.8	190.7
OCSD PVDF 200 eff 3	130.8	765	206.1	207.6	204.3
Average	**135.9667**	**1139.667**	**186.7**	**187.8333**	**186.7**

Table 20. Particle analysis of SMWD feed samples used in PVDF1 flux analysis

Feed Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
SMWD Mem 1 unfilt feed 1	1528.6	247.6	416.5	572.3	105.8
SMWD Mem 1 unfilt feed 2	1581.7	247.2	422.1	366.2	35.99
SMWD Mem 1 unfilt feed 3	1557.8	240.6	557.8	612.6	38.48
Average	**1556.03**	**245.133**	**465.467**	**517.033**	**60.09**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
SMWD unfilt feed (redo) 1	1499.6	292.9	475.7	504.5	43.63
SMWD unfilt feed (redo) 2	1510.2	309.4	322.9	346.2	83.21
SMWD unfilt feed (redo) 3	1482.6	268.7	358.3	412.3	85.88
Average	**1497.47**	**290.333**	**385.633**	**421**	**70.9067**
SMWD Mem 2 450 feed 1	687.9	180.3	318.7	497.8	127.6
SMWD Mem 2 450 feed 2	678.3	170.3	317.7	471.9	103.3
SMWD Mem 2 450 feed 3	672.4	169.2	348	562.2	74.76
Average	**679.533**	**173.267**	**328.133**	**510.633**	**101.887**
SMWD Mem 3 200 feed 1	274.2	183.9	150.9	147	130.4
SMWD Mem 3 200 feed 2	285.8	186.5	145.2	139.2	120.8

SMWD Mem 3 200 feed 3	280.3	165.6	158.3	152.7	126.3
Average	**280.1**	**178.667**	**151.467**	**146.3**	**125.833**
SMWD Mem 4 100 feed 1	111.4	190.9	132.3	124	107.1
SMWD Mem 4 100 feed 2	112.3	167.2	129.6	121.3	105.5
SMWD Mem 4 100 feed 3	115.4	167	131.9	122.2	103.5
Average	**113.033**	**175.033**	**131.267**	**122.5**	**105.367**

Table 21. Particle analysis of SMWD permeate samples used in PVDF1 flux analysis

Permeate					
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
SMWD Mem 1 unfilt eff 1	224.8	562.3	357.8	364.4	352.6
SMWD Mem 1 unfilt eff 2	233.1	515.8	357.7	364.8	351.7
SMWD Mem 1 unfilt eff 3	222.6	490.5	371.2	380.5	362.3
Average	**226.833**	**522.867**	**362.233**	**369.9**	**355.533**
Sample Name	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
SMWD unfilt eff (redo) 1	339.1	528.2	349.5	358.4	340.8
SMWD unfilt eff (redo) 2	342.7	517.5	353.9	363	345.3
SMWD unfilt eff (redo) 3	327.4	470	330.9	340.8	318.7
Average	**336.4**	**505.233**	**344.767**	**354.067**	**334.933**
SMWD Mem 2 450 eff 1	22.8	540.3	130.1	125	114
SMWD Mem 2 450 eff 2	18.1	2112	76.97	75.73	73.95

SMWD Mem 2					
450 eff 3	16.4	1892	65.56	64.17	62.44
Average	**19.1**	**1514.77**	**90.8767**	**88.3**	**83.4633**
SMWD Mem 3					
200 eff 1	156.5	681.8	359.6	365	356.3
SMWD Mem 3					
200 eff 2	155.4	727.8	328	332.7	325.1
SMWD Mem 3					
200 eff 3	146.3	706	357	362.7	353
Average	**152.733**	**705.2**	**348.2**	**353.467**	**344.8**
SMWD Mem 4					
100 eff 1	115.2	1433	341.6	343.5	343.3
SMWD Mem 4					
100 eff 2	115.4	1204	332.8	335.7	332.3
SMWD Mem 4					
100 eff 3	119.6	1135	353.7	357.6	353.2
Average	**116.733**	**1257.33**	**342.7**	**345.6**	**342.933**

Table 22. Particle analysis of Alum coagulation experiment

Alum Concentration	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
0	1779.87	1170.00	464.63	391.20	54.75
1	1856.97	849.70	341.87	350.70	332.03
10	2002.20	1008.83	498.97	467.40	64.87
20	1749.40	751.53	387.63	400.83	373.10
40	1526.60	720.97	459.47	469.27	305.97
60	1582.67	591.73	726.73	853.87	143.77
80	1488.73	589.27	608.17	699.07	111.30
450 filtered					
0	204.13	167.40	299.40	260.17	42.51
1	220.50	155.03	280.00	219.67	47.24
10	128.17	181.47	290.70	218.23	26.57
20	98.17	255.97	190.27	127.94	55.42
40	69.87	389.83	185.40	186.93	163.93
60	39.63	278.80	212.17	148.53	42.71
80	42.50	813.47	111.26	108.88	102.26
Flux anlaysis					

0	36.80	2146.00	109.33	108.88	107.26
1	50.80	351.27	1157.00	1017.50	49.22
10	41.00	1090.87	369.23	379.43	358.03
20	32.27	3885.00	133.23	133.82	132.29
40	81.10	1229.00	469.30	482.23	457.10
60	43.23	1204.00	288.00	251.47	193.52
80	32.77	2410.67	164.81	110.31	64.36

Table 23. COD, turbidity, and pH of alum coagulation experiment

Unfiltered			
Alum Concentration	COD	Turbidity	pH
0	115.00	52.00	7.58
1	89.00	39.00	7.56
10	87.00	38.00	7.43
20	88.00	32.00	7.37
40	67.00	21.00	7.20
60	60.00	18.00	7.09
80	51.00	14.00	6.87

Table 24. COD, and turbidity results of 450nm filtered alum coagulation samples

Filtered		
Alum Concentration	COD	Turbidity
0	58.00	10.00
1	52.00	10.00
10	44.00	8.00
20	41.00	8.00
40	45.00	7.00
60	40.00	7.00
80	42.00	5.00

Table 25. Particle analysis of ferric chloride coagulation experiment

Concentration	Mean Count	Z-Average	Intensity Mean	Volume Mean	Number Mean

	Rate (kcps)	(d.nm)	(d.nm)	(d.nm)	(d.nm)
unfiltered					
0	1901.00	1079.00	516.30	505.50	70.98
10	1980.50	827.80	507.50	458.70	54.36
20	1632.70	687.90	367.60	378.60	355.30
40	1209.20	573.30	797.60	906.50	69.93
60	929.10	512.50	645.90	821.10	348.50
80	851.90	612.90	563.90	631.60	88.27
100	735.60	695.50	529.90	525.50	56.20
450 nm filtered					
0	168.47	193.70	170.50	179.07	84.90
10	143.53	243.23	255.07	211.87	63.08
20	142.20	249.33	132.67	107.38	81.37
40	90.13	157.10	330.83	282.47	38.32
60	84.83	175.07	410.43	449.93	47.60
80	65.50	164.00	351.07	388.23	56.22
100	55.00	171.30	314.80	378.97	67.27
Flux analysis					
0	22.27	733.60	271.91	7.27	5.81
10	47.60	1405.00	439.03	448.03	278.52
20	160.27	1745.00	602.63	615.27	598.60
40	24.67	2676.00	157.07	157.63	155.90
60	164.23	878.33	323.90	331.07	316.10
80	17.87	2055.00	247.80	250.07	247.37
100	31.30	1385.67	391.47	165.15	23.55

Table 26. COD, turbidity, and pH of ferric chloride coagulation experiment

Unfiltered Coagulant Concentration	COD	Turbidity	pH
0	148	55.00	7.75
10	89.00	35.00	7.54
20	77.00	27.00	7.44
40	65.00	20.00	7.26
60	56.00	15.00	7.13
80	51.00	14.00	6.95
100	41.00	10.00	6.84

Table 27. COD, and turbidity results of 450nm filtered ferric chloride coagulation samples

Filtered Coagulant Concentration	COD	Turbidity
0	48.00	7.00
10	41.00	8.00
20	42.00	7.00
40	39.00	7.00
60	36.00	6.00
80	32.00	4.00
100	35.00	5.00

Table 28. Particle analysis of the polymer coagulation experiment

Concentration	Mean Count Rate (kcps)	Z-Average (d.nm)	Intensity Mean (d.nm)	Volume Mean (d.nm)	Number Mean (d.nm)
0	1497.5	799.0	396.6	294.1	53.0
0.5	1531.7	887.7	350.1	227.9	43.1
1	1724.1	926.0	347.8	267.4	111.4
5	1738.1	899.5	331.8	339.5	322.8
10	1834.3	833.7	417.4	366.2	160.7
10	1694.4	601.3	432.4	399.9	168.5
15	1774.0	716.1	479.2	451.3	65.7
20	1762.4	680.2	481.3	450.0	61.8
30	1615.4	558.0	496.9	566.1	395.0
50	1216.6	546.8	572.6	668.6	100.7
100	377.2	574.7	438.6	481.5	175.5
0	149.1	151.7	324.0	230.6	27.6
0.5	142.1	151.6	320.8	239.3	32.0
1	130.1	143.0	294.5	281.1	48.4
5	150.9	172.6	151.6	116.2	72.8
10	126.4	146.2	303.9	213.9	29.6
15	124.3	146.2	295.2	185.3	24.2
20	100.2	201.6	308.9	251.0	37.2
30	80.3	397.9	356.8	363.8	57.0
50	81.7	181.4	183.6	135.9	67.7

100	41.4	144.3	272.0	374.1	88.4
0	22.1	1870.0	180.6	82.2	80.8
1	28.0	1411.0	197.1	198.5	196.3
5	37.0	2339.0	178.8	179.9	177.1
10	48.4	1384.0	402.2	252.8	38.3
30	24.7	1864.0	342.8	344.8	344.5
50	27.3	3613.0	221.7	55.2	31.3
100	14.5	1848.0	136.8	135.5	130.8

Table 29. COD, turbidity, and pH of the polymer coagulation experiment

Unfiltered Coagulant Concentration	COD	Turbidity	pH
0	102	46.00	8.01
0.5	86.00	39.00	8.01
1	85.00	44.00	8.00
5	88.00	43.00	7.98
10	88.00	44.00	7.96
10	85.00	39.00	7.98
15	86.00	39.00	7.97
20	79.00	37.00	7.95
30	73.00	33.00	7.93
50	61.00	20.00	7.92
100	43.00	11.00	7.88

Table 30. COD, and turbidity results of 450nm filtered polymer coagulation samples

Filtered Coagulant Concentration	COD	Turbidity
0	46.00	10.00
0.5	43.00	11.00
1	51.00	9.00
5	44.00	11.00
10	42.00	10.00
15	42.00	10.00

20	39.00	8.00
30	36.00	8.00
50	31.00	8.00
100	29.00	7.00

Table 31. Flux analysis of alum coagulation samples

flux (mL/m2/s)						ALUM	
time (mins)	control	1 mg/L	10 mg/L	20 mg/L	40 mg/L	60 mg/L	80 mg/L
0.00							
1.99	57.96	48.41	51.53	73.09	93.94	106.04	110.03
3.99	33.07	25.35	34.70	47.77	62.03	69.31	71.76
5.99	26.23	21.87	30.53	37.89	50.79	56.91	59.45
7.99	21.95	20.33	27.30	35.21	43.03	50.11	52.55
9.99	20.38	18.08	25.32	31.73	40.84	45.56	47.07
11.99	19.39	17.52	22.74	28.60	36.38	41.02	43.65
13.99	17.55	15.84	22.28	27.01	35.00	39.17	41.08
15.99	16.98	16.07	23.00	24.62	32.34	36.99	38.50
17.99	14.72	14.69	19.09	24.04	30.56	34.60	36.79
19.99	14.66	13.36	18.46	22.88	30.38	33.78	35.10
21.99	14.16	16.16		23.25		32.33	34.97
23.99	13.76						
25.99	13.11						
27.99	12.67						

Table 32. Energy analysis of alum coagulation samples

Energy Required							
time (mins)	control	1 mg/L	10 mg/L	20 mg/L	40 mg/L	60 mg/L	80 mg/L
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.99	6.18	7.39	6.95	4.90	3.81	3.38	3.25
3.99	10.83	14.12	10.32	7.49	5.77	5.17	4.99
5.99	13.65	16.37	11.73	9.45	7.05	6.29	6.02
7.99	16.31	17.61	13.11	10.17	8.32	7.14	6.81
9.99	17.57	19.80	14.14	11.28	8.77	7.86	7.61
11.99	18.47	20.44	15.74	12.52	9.84	8.73	8.20
13.99	20.40	22.60	16.07	13.25	10.23	9.14	8.72
15.99	21.08	22.28	15.56	14.54	11.07	9.68	9.30
17.99	24.32	24.37	18.75	14.89	11.72	10.35	9.73
19.99	24.41	26.80	19.39	15.65	11.79	10.60	10.20
21.99	25.28	22.16		15.40		11.07	10.24

Table 33. Flux analysis of ferric chloride coagulation samples

flux (L/m2/s)							FeCl
time (mins)	control	10 mg/L	20 mg/L	40 mg/L	60 mg/L	80 mg/L	100 mg/L

0.00	68.14	60.66	79.30	90.92	104.27	117.81	219.15
1.99	26.83	36.74	46.73	51.49	58.64	69.32	82.42
3.99	22.14	31.49	38.77	41.98	48.52	57.25	69.78
5.99	19.65	27.83	33.21	37.36	42.63	50.33	60.92
7.99	18.48	25.07	30.63	33.70	39.45	44.79	56.47
9.99	16.75	23.89	28.30	32.01	36.71	41.76	52.90
11.99	15.90	22.02	26.47	28.81	34.46	39.35	49.36
13.99	15.43	21.44	23.71	27.95	32.28	37.30	46.83
15.99	13.55	19.98	23.70	27.00	28.86	35.21	44.47
17.99	13.24	19.46	22.71	25.50	29.14	34.01	43.20
19.99					28.57	32.84	

Table 34. Energy analysis of ferric chloride coagulation samples

	Energy Consumption							FeCl
time (mins)	DI water	control	10 mg/L	20 mg/L	40 mg/L	60 mg/L	80 mg/L	100 mg/L
0.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.99		5.82	6.54	5.00	4.36	3.80	3.37	1.81
3.99		14.78	10.80	8.49	7.70	6.76	5.72	4.81
5.99		17.92	12.60	10.23	9.45	8.17	6.93	5.68
7.99		20.18	14.25	11.94	10.62	9.30	7.88	6.51
9.99		21.46	15.82	12.95	11.77	10.05	8.86	7.02
11.99		23.68	16.60	14.02	12.39	10.80	9.50	7.50
13.99		24.94	18.01	14.98	13.77	11.51	10.08	8.04
15.99		25.71	18.50	16.73	14.19	12.29	10.63	8.47
17.99		29.27	19.85	16.73	14.69	13.74	11.26	8.92
		29.96	20.38	17.46	15.55	13.61	11.66	9.18

Table 35. Flux analysis of polymer coagulation samples

	flux (mL/s)						Poly
time (mins)	control	1 mg/L	5 mg/L	10 mg/L	30 mg/L	50 mg/L	100 mg/L
0.00							
1.99	74.41	56.92	63.27	53.67	87.04	103.45	195.34
3.99	29.56	27.44	36.30	31.64	50.13	66.50	123.50
5.99	23.59	23.68	30.54	27.77	41.33	55.42	100.34
7.99	21.27	21.18	27.73	24.93	36.08	49.43	83.79
9.99	19.28	18.70	25.28	23.29	32.68	44.74	72.80
11.99	17.58	17.52	23.76	20.55	30.04	39.95	66.57
13.99	17.04	17.01	22.76	19.24	28.40	38.15	61.93
15.99	15.51	16.30	21.36	19.88	26.28	36.08	60.56
17.99	14.93	15.81	19.54	18.63	25.46	34.50	55.85

19.99	15.13	13.81	19.03	18.02	24.35	32.96	53.60
21.99		14.11	18.36			32.15	

Table 36. Energy analysis of polymer coagulation samples

	flux (%)						poly
time (mins)	control	1 mg/L	5 mg/L	10 mg/L	30 mg/L	50 mg/L	100 mg/L
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.99	5.30	6.92	6.23	7.34	4.53	3.81	2.02
3.99	13.33	14.36	10.85	12.45	7.86	5.93	3.19
5.99	16.70	16.64	12.90	14.19	9.54	7.11	3.93
7.99	18.53	18.61	14.21	15.81	10.92	7.97	4.70
9.99	20.44	21.07	15.59	16.92	12.06	8.81	5.41
11.99	22.41	22.50	16.58	19.18	13.12	9.86	5.92
13.99	23.12	23.17	17.32	20.49	13.87	10.33	6.36
15.99	25.40	24.18	18.45	19.82	14.99	10.92	6.51
17.99	26.40	24.93	20.16	21.16	15.48	11.42	7.06
19.99	26.04	28.54	20.71	21.87	16.18	11.96	7.35
21.99		27.93	21.46			12.26	

Table 37. Energy analysis of OCSD polypropylene samples

	Energy (%)						
time (s)	DI water	unfiltered	400nm	200nm	100nm	3.5nm	2.5nm
0.00		1.00	1.00	1.00	1.00	1.00	1.00
1.99		6.96	2.55	1.24	1.09	1.34	1.37
3.99		17.82	3.77	1.83	1.51	1.49	1.31
5.99		28.73	4.83	2.37	1.90	1.68	1.33
7.99		39.13	5.67	2.89	2.26	1.86	1.32
9.99		44.98	6.63	3.31	2.61	2.01	1.31
11.99		52.23	7.24	3.71	2.90	2.00	1.27
13.99		66.53	8.03	4.09	3.20	2.03	1.29
15.99		74.85	8.87	4.38	3.39	2.08	1.31
17.99		78.60	9.55	4.71	3.70	2.11	1.31
19.54			10.13	4.97	4.02	2.09	1.32
21.99			10.61		4.17	2.05	1.32
23.99					4.37	1.97	1.34

Table 38. Energy analysis of SMWD polypropylene samples

	Energy (%)						
time (mins)	DI water	unfiltered	450nm	200nm	100nm	3.5nm	2.5nm
0.00		1.00	1.00	1.00	1.00	1.00	1.00

1.99	3.81	2.14	2.20	2.04	1.21	1.20
3.99	8.98	4.64	4.23	3.56	1.51	1.19
5.99	13.02	6.48	5.36	4.50	1.76	1.19
7.99	13.70	8.02	6.59	4.87	1.88	1.19
9.99	17.10	9.19	7.48	5.26	1.90	1.19
11.99	16.87	10.07	8.26	5.45	1.83	1.18
13.99	19.09	11.48	8.82	5.62	1.86	1.19
15.99	21.96	12.66	9.47	5.78	1.88	1.20
17.99	20.91	13.07	10.11	5.99	1.88	1.14
19.54	22.68	13.87	10.36	5.98	1.85	1.15
21.99	23.39	14.52	10.77	6.16	1.85	1.16

Table 39. Energy analysis of IRWD polypropylene samples

	energy (%)						
time (s)	DI water	unfiltered	450nm	200nm	100nm	3.5nm	2.5nm
0.00		1.00	1.00	1.00	1.00	1.00	1.00
1.99		1.64	1.34	1.32	1.18	1.26	1.29
3.99		3.05	2.23	2.12	1.75	1.37	1.23
5.99		4.40	3.00	2.85	2.29	1.50	1.23
7.99		5.81	3.72	3.51	2.82	1.67	1.23
9.99		7.04	4.38	4.13	3.27	1.84	1.21
11.99		8.18	5.00	4.59	3.66	2.03	1.22
13.99		9.86	5.53	5.06	4.11	2.25	1.21
15.99		10.05	6.36	5.49	4.40	2.27	1.22
17.99		10.72	6.43	5.88	4.76	2.40	1.20
19.54		11.42	7.05	6.34	5.04	2.37	1.22
21.99			7.32	6.55	5.43	2.30	1.18

Table 40. Energy analysis of IRWD PVDF1 samples

	energy (%)					
time (mins)	unfiltered	450nm	200nm	100nm	3.5nm	2.5nm
0.00	1.00	1.00	1.00	1.00	1.00	1.00
1.99	1.34	#N/A	0.99	1.06	1.24	1.18
3.99	1.37	1.07	0.91	0.98	1.21	1.14
5.99	1.36	1.05	0.91	0.95	1.18	1.12
7.99	1.42	1.00	0.92	0.93	1.10	1.05
9.99	1.46	1.04	0.93	0.94	1.09	1.02

11.99	1.58	1.03	0.95	0.95	1.07	1.08
13.99	1.37	1.04	0.96	0.94	1.03	1.02
15.99	1.48	1.07	0.98	0.95	1.03	1.01
17.99	1.56	1.08	0.99	0.96	1.04	1.00
19.99	1.57	1.13	1.03	0.99	1.04	0.99
21.99	1.65	1.11	1.03	0.98	1.03	0.98
23.99	1.60	1.12	1.03	0.98	1.03	0.97
25.99	1.72	1.13	1.05	0.99	0.99	0.96
27.99	1.66	1.17	1.06	0.99	1.01	0.94
29.99	1.69	1.17	1.07	0.95	0.99	0.94
31.99	2.01	1.19	1.08	1.00	0.98	0.97
33.99	1.95	1.21	1.09	1.02	1.00	0.95
35.99	1.91	1.22	1.10	1.02	0.97	0.93
37.99	#N/A	1.23	1.11	1.02	0.98	0.93
39.99	1.95	1.28	1.16	1.03	0.98	0.92
41.99	1.90	1.27	1.14	1.03	0.98	0.93
43.99	1.92	1.27	1.16	1.05	0.96	0.96
45.99	1.89	1.30	1.17	1.08	0.97	0.91
47.99	1.92	1.31	1.18	1.05	0.97	0.90
49.99	1.94	1.32	1.19	1.07	0.97	0.91
51.99	1.96	1.34	1.18	1.06	0.96	0.89
53.99	1.96	1.35	1.20	1.07	0.97	0.90
55.99	2.00	1.36	1.21	1.08	0.98	0.89
57.99	2.00	1.40	1.22	1.08	0.96	0.89
59.99	2.07	1.39	1.22	1.10	0.96	0.89

Table 41. Energy analysis of OCSD PVDF1 samples

	energy (%)				
time (mins)	unfiltered	450nm	200nm	3.5nm	2.5nm
0.00	1.00	1.00	1.00	1.00	1.00
1.99	1.31	0.95	0.96	1.47	1.26
3.99	1.30	0.86	0.76	1.36	1.17
5.99	1.33	0.86	0.89	1.32	1.14
7.99	1.39	0.87	0.87	1.30	1.14
9.99	1.41	0.89	0.88	1.36	1.14
11.99	1.46	0.91	0.90	1.28	1.16
13.99	1.43	0.93	0.90	1.27	1.12
15.99	1.51	0.95	0.93	1.26	1.11
17.99	1.51	0.97	0.93	1.26	1.12
19.99	1.59	1.00	0.95	1.28	1.10
21.99	1.67	1.01	0.95	1.26	1.09
23.99	1.60	1.03	0.97	1.25	1.09
25.99	1.62	1.05	0.99	1.25	1.08
27.99	1.65	1.06	1.00	1.25	1.08
29.99	1.67	1.12	1.02	1.25	1.09
31.99	1.69	1.11	1.02	1.25	1.13
33.99	1.75	1.13	1.05	1.31	1.08

35.99	1.74	1.14	1.06	1.25	1.07
37.99	1.77	1.15	1.10	1.24	1.06
39.99	1.95	1.13	1.09	1.25	1.06
41.99	1.84	1.20	1.12	1.26	1.06
43.99	1.86	1.21	1.11	1.24	1.06
45.99	1.92	1.24	1.13	1.25	1.07
47.99	1.92	1.14	1.15	1.24	1.05
49.99	1.94	1.29	1.15	1.25	1.05
51.99	1.98	1.28	1.18	1.32	1.06
53.99	1.97	1.28	1.18	1.25	1.04
55.99	1.98	1.31	1.02	1.24	1.05
57.99	2.11	1.32	1.23	1.24	1.09
59.99	2.02	1.35	1.23		1.05

Table 42. Energy analysis of SMWD PVDF1 samples

	energy (%)					
time (mins)	unfiltered	450nm	200nm	100nm	3.5nm	2.5nm
0.00	1.00	1.00	1.00	1.00	1.00	1.00
1.99	1.67	1.50	1.17	1.42	1.13	1.14
3.99	1.38	1.51	1.15	1.18	1.07	1.21
5.99	1.60	1.46	1.18	1.18	1.05	1.13
7.99	1.49	1.51	1.21	1.20	1.04	1.11
9.99	1.68	1.57	1.22	1.17	1.03	1.09
11.99	1.70	1.66	1.30	1.24	1.01	1.08
13.99	2.10	1.69	1.35	1.21	1.03	1.06
15.99	1.79	1.79	1.38	1.20	0.99	1.03
17.99	2.12	1.85	1.42	1.22	1.02	1.06
19.99	2.16	1.87	1.46	1.30	1.00	1.02
21.99	2.25	1.99		1.33	1.00	1.02

Table 43. Energy analysis of SMWD PVDF2 samples

	energy (%)				
time (mins)	unfiltered	450nm	200nm	3.5nm	2.5nm
0.00	1.00	1.00	1.00	1.00	1.00
1.99	1.72	1.98	1.34	1.78	1.39
3.99	2.38	2.27	1.60	1.93	1.39
5.99	2.86	2.45	1.79	1.95	1.40
7.99	3.22	2.60	1.98	1.85	1.39
9.99	3.63	2.75	2.09	1.88	1.33

11.99	3.86	2.93	2.22	1.84	1.34
13.99	4.15	3.00	2.33	1.83	1.35
15.99	4.59	3.12	2.43	1.81	1.44
17.99	4.73	3.22	2.57	1.82	1.50
19.99	5.14	3.30	2.63	1.80	1.34
21.99	5.18	3.47	2.74	1.77	1.31
23.99	5.44	3.53	2.80	1.82	1.26
25.99	5.82	3.61	2.90	1.85	1.32
27.99	5.84	3.66	3.37	1.79	1.31
29.99	6.04	3.74	3.10	1.66	1.32
31.99	6.43	3.89	3.12	1.69	1.31
33.99	6.38	3.87	3.17	1.70	1.30
35.99	6.59	3.99	3.23	1.74	1.30
37.99	7.11	4.03	3.28	1.72	1.29
39.99	6.97	4.11	3.42	1.73	1.29
41.99	7.09	4.24	3.44	1.73	1.28
43.99	7.67	4.33	3.50		1.27